V. Rydnik

ABC's OF QUANTUM MECHANICS

On the threshold of the twentieth century physicists began penetrating into the invisible, soundless world of atoms, atomic nuclei and elementary particles. Following experiment came the theory of this new kingdom—quantum mechanics, which has been a faithful guide in physics for 60 odd years now.

Customary laws frequently cease to operate in this bizarre world. Particles lose their dimensions and acquire the properties of waves; waves, in turn, begin to act like particles. Electrons and the other building blocks of matter pass through insuperable barriers or vanish outright, leaving photons in their place.

These fantastic happenings are explained by quantum mechanics. This book deals with the origins and development of quantum physics. It describes the basic concepts of quantum mechanics and tells how the new theory deciphered the secrets of the structure of atoms, molecules, crystals, and atomic nuclei, and how this scientific tool is being applied to solve the problem of the most fundamental property of matter, that of the interaction of particles and the interrelationships of matter and fields.

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ИЗДАТЕЛЬСТВО
«СОВЕТСКАЯ РОССИЯ»
МОСКВА

V. RYDNIK

ABC's OF QUANTUM MECHANICS

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At the turn of the century, physics entered into a new world, the invisible silent world of atoms, atomic nuclei and elementary particles. Our twentieth century then produced the theory that has been serving physicists so faithfully for over sixty years—quantum mechanics.

The landscape of the new world is quite unlike our own. So different that physicists frequently lack words to describe it. Quantum mechanics had to create new conceptions for the world of the ultrasmall, bizarre conceptions beyond the scope of pictorial imagery.

Customary physical laws cease to operate in the new world. Particles lose their dimensions and acquire the properties of waves. Then again, waves begin to act like particles. Electrons and the other building stones of matter can pass through impenetrable barriers, or they can vanish altogether leaving only photons in their place. Those are the things quantum mechanics dealt with.

This book will tell you about the origin and development of quantum mechanics, about its new concepts. It will describe how the new theory deciphered the secrets of the structure of atoms, molecules, crystals, atomic nuclei, and how quantum mechanics is dealing with the problem of the most fundamental of all properties of matter—the interaction of particles and the relationships between fields and matter.

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From Classical Mechanics to Quantum Mechanics

In Lieu of an Introduction

Atomic energy. Radioactive isotopes. Semiconductors. Elementary particles. Masers. Lasers. All quite familiar terms, yet the oldest is hardly twenty-five years of age. They are all children of twentieth-century physics.

In this age, knowledge is advancing at a fantastic rate, and every new step opens up fresh vistas. The old sciences are going through a second youth. Physics has pushed out ahead of all others and is pioneering into the unknown. As the front broadens, the attack slows up only to make renewed thrusts forward.

To get at the secrets of nature, physics has had to find powerful instruments, to devise precise and convincing experiments. At the physics headquarters are hundreds and thousands of theoreticians mapping out the offensive and studying the trophies captured in the experiments. This is no struggle in the dark. The field of battle is lighted up with powerful physical theories. The strongest searchlights of pres-

ent-day physics are the theory of relativity and quantum mechanics.

Quantum mechanics came in with the twentieth century. Date of birth: December 17, 1900. It was on this day that the German physicist Max Planck reported to a meeting of the Berlin Academy of Sciences Physical Society on his attempt to overcome one of the difficulties of the theory of thermal radiation.

Difficulties are a common thing in science. Every day scientists come up against them. But Planck's encounter had a very special significance, for it foreshadowed the development of physics for many years to come.

An enormous tree of new knowledge has grown out of the seminal ideas expressed by Planck, which served as a starting point for amazing discoveries far beyond the imagination of the wildest science-fiction writers. Out of Planck's concepts grew quantum mechanics, which opened up an entirely new world—the world of the ultrasmall, of atoms, atomic nuclei and elementary particles.

The Outlines of the New World

But didn't people know anything about this atom before the twentieth century? In a way they did, that is, they had guessed and conjectured.

The inquisitive human mind had speculated upon these things and had long imagined what became a real thing only many centuries later.

In ancient times, long before the first travellers laid their paths of discovery, man had guessed that there were people and animals and land beyond the little area in which he lived.

In the same way, people felt that there existed a world of the ultrasmall long before it was actually discovered. One did not need to go far in search of this new world, for it was right at hand, lying around him in all things.

In olden times, thinkers had meditated on the way nature had produced the world around us out of something quite formless. How was it, they queried, that it came to be inhabited by its great diversity of things. Might it not be that nature worked like a builder that makes large houses out of small stones? Then what are these stones?

Enormous mountains are weathered away by the water, the wind, and mysterious volcanic forces. The rocks that come away are in time broken down into small pieces. Hundreds and thousands of years pass, and these are pulverized into dust.

Is there no limit to this dividing and subdividing of matter? Are there particles so small that even nature is no longer able to break them up? The answer was YES. So said the ancient philosophers Epicurus, Democritus and others. These particles were given the name 'atom'. Their chief property was that no further division is possible. The word 'atom' in Greek means 'nondivisible'.

What did an atom look like? In those times, this question remained unanswerable. Atoms might be in the form of solid impenetrable spheres, yet they might not be. Then again: How many different varieties are there? Maybe a thousand, yet perhaps only one. Some philosophers (the Greek Anaximander, for one) believed that there were probably four. They believed that the entire universe consisted of four elements—

water, air, earth, and fire. In turn, these elements were thought to consist of atoms.

One might now think that with information as meagre as this there could be no talk of any progress. True, yet the first steps of science are usually in breadth and not in depth. So many things surround man! The first job is to find out how they are related to one another, and then, only later, how they are constructed.

The conception of atoms in an age when science was still in its infancy was a conjecture of genius. But it was only a conjecture which did not follow from any kind of observations and was not supported by any kind of experiments.

The atoms were forgotten for a very long time.

They were recalled, or rather they were invented once again, only at the beginning of the nineteenth century. And not by physicists, but by chemists.

The start of last century was an interesting time both for the historian of society—Napoleon was recarving the boundaries of European states —and for the historian of science—in the quiet of the few laboratories that existed in those days there was in progress a radical reevaluation of the nature of things. Conceptions that had appeared quite stable were being reconsidered.

Young in England and Fresnel in France had laid the foundation of the wave theory of light. Abel in Norway and Galois in France had put the first stones in the mighty edifice of modern algebra. The Frenchman Lavoisier and the Englishman Dalton demonstrated that chemistry is capable of wonders. The chemists, physicists and mathematicians of that time made a whole series of outstanding discoveries that prepared the way for the flourishing of the exact sciences in the latter half of the nineteenth century.

An unknown English scholar Prout in 1815 expressed the view that there exist minute particles which can participate in the most diverse chemical reactions without being destroyed and reconstructed. These were obviously atoms.

During those same years, the illustrious French scientist Lagrange put classical mechanics in that complete and elegant form in which—it was later found—there was no place for atoms.

The Temple of Classical Mechanics

In science, nothing appears from nowhere. And quantum mechanics may justly be called the brain child of classical mechanics, which began with Newton.

True, it is not entirely right to attribute the creation of classical mechanics to Newton alone. Many great minds during the Renaissance were engaged in problems that later formed the basis of classical mechanics: Leonardo da Vinci, Galileo Galilei, the Dutch mathematician Simon Stevin and the Frenchman Blaise Pascal. Out of all the scattered studies of the motions of bodies, Newton constructed a single unified and harmonious theory.

We know the exact date when classical mechanics was born. It was the year 1687, when Newton's book "Philosophia Naturalis Principia Mathematica" ("The Mathematical Principles of Natural Philosophy") appeared in London. In those days the natural sciences still went by the name philosophy.

In his work, Newton formulated for the first time the three basic principles of classical mechan-

ics, later called Newton's three laws which every schoolchild studies.

The edifice of mechanics that Newton built goes far beyond these three laws, and has long since been completed. From the vantage point of modern science, it looks like this.

In the enormous void of space inhabited by numerous and diverse objects, from gigantic stars to minute dust particles, there was a point in the distant past when the entire universe was without motion, in a state of complete rest.

It was god, who regarding in amazement the fruit of his creation, gave the first 'impulse' and breathed life into the world. This exhausted god's duties. From then on all the bodies in the universe began to move and interact according to definite laws. The number of such laws was great but in the final analysis they could all be reduced to several basic laws, which included the three laws of Newton.

From this minute on there was never anything accidental. Everything was predetermined. Nothing arbitrary was possible any more. From then on there was perfect harmony in this symphony of the universe.

For more than a century after Newton this supreme orderliness of the universe based on Newtonian mechanics was extremely satisfying to all physicists. They were pacified each time some new piece of the universe was found to fit nicely into the theory. And for quite some time nature allowed itself to be treated this way.

But not for long. Scientists were soon convinced that there is nothing less stable than hardened dogmas. Facts began to appear that simply would not fit into the old framework.

By the end of the nineteenth century Newtonian mechanics was in a crisis. It gradually became clear that this crisis signified the fall of universal determinism, scientifically called the principle of mechanical determinism. The universe was not so simple after all, and it wasn't wound up for all time.

Quantum mechanics brought with it not only new knowledge. It gave a radically different interpretation to the phenomena of the world. For the first time, science gave full recognition to the accidental.

And perhaps physicists are not to blame for being taken aback. Though it was only the eternal determinism which they themselves had concocted that gave way, physicists seemed to think that it was determinism as such that was crumbling, that the universe was governed by absolute anarchy, and that things no longer obeyed exact laws.

It took quite some time before physics found its way out of the deep crisis.

The Temple Collapses

Curiosity killed a cat. The saying is probably applicable to theories as well. Even if today the theory appears quite correct and capable of explaining all the facts.

A theory puts in its appearance at a certain stage in the development of science, when the latter has made a study of a wide range of phenomena. The aim of the theory is to give an explanation from some one point of view.

But the very same theory proves insufficient and even erroneous when fresh facts are dis-

covered that do not fit into its narrow framework.

Classical mechanics was entirely satisfactory as long as physics was confined to mechanics. But the nineteenth century saw physics attack a new broad front: thermal processes, which gave rise to thermodynamics; light, which gave rise to optics; electric and magnetic phenomena, which served as a starting point for electrodynamics. For a time, physics remained in a rather contented state. All new discoveries continued to fit neatly into the existing moulds.

However, as the edifice of classical physics grew upwards, its enormous front gave signs of fatigue, sinister cracks appeared, and finally the entire structure began to crumble under the bombardment of new facts.

One of these most fundamental facts was the remarkable constancy of the velocity of light. The most careful and objective experiments demonstrated that the behaviour of light is radically different from what had been observed in all other known areas.

To fit the behaviour of light into the framework of classical physics, scientists had to devise a medium called the ether, which, by the rules of classical physics, would possess simply fantastic properties. We shall come back to this ether later on and examine it in more detail. But the new ether could not save the old physics.

Another stumbling block to classical physics was the thermal radiation of heated bodies.

Then, finally, the discovery of radioactivity. This had the most shattering effect on classical physics during the last years of its undivided rule, for the mysterious processes of radioactivity not only smashed atomic nuclei, but exploded the

very basis of physics—those principles that had appeared so obvious from the standpoint of common sense. Out of these cracks in the structure of classical mechanics grew the theory of relativity and the quantum theory.

How the New Theory was Named

Quantum mechanics was born at the turn of the century. But why this name? Actually, the term but feebly reflects the contents of those things which the new physics dealt with.

Probably not a single branch of physics has escaped a certain vagueness in terminology. There are many reasons for this, but they are primarily of a historical nature.

First of all, why mechanics? There was nothing mechanical in the new theory, and as we shall see later on, there couldn't be. The word 'mechanics' is justified only in that it is used in a general sense, like we speak of the 'mechanics of a watch' meaning the principle of operation. The conceptual range of quantum mechanics is better covered by the broad definition of physics itself.

Secondly, why quantum? Quantum in Latin means 'discrete portion' or 'quantity'. Further on we shall see that the new science does actually deal with 'discreteness' in the properties of the surrounding world. That is one of its basic principles. On the other hand, as we shall see, this discreteness is not at all general, and is not found everywhere or at all times.

What is more, it is only one side of the medal. A no less peculiar aspect is the duality of the properties of matter. The dual nature of matter

lies in the fact that one and the same entity (object) combines the properties of particles and waves.

The new science was refined to 'wave mechanics'. But here again we have only half of it—there is no mention of quanta.

We conclude that none of the names of the new physical theory was satisfactory. But couldn't something be thought up more in keeping with the actual contents of the subject?

The introduction of new terms in science is a laborious and thankless job. New terms come in slowly and change still more slowly. Physicists understand the new meaning that these terms carry and so it is for us to learn them.

Physicists Build Models

Imagine the motion of a ball along a rope that you are whirling round your head. It is obviously quite simple because you can see everything with your own eyes. That is exactly how classical physics developed—out of the observations of objects and phenomena that surround us.

Roll a ball along a smooth horizontal table. It continues to move after the action of the hand has ceased, that is, after the force has ceased to operate. This and similar observations gave rise to the law of inertia that was enunciated by Newton as the first basic law of mechanics.

A ball will not begin to move until pushed by the hand or hit by another ball. A ball moving over a smooth table and a ball at rest have one thing in common: they are not acted upon by any forces.

On the rope, however, the ball is all the time acted upon by a force that deflects it from the rectilinear path inherent in free motion. That same ball at rest on the table will, under the action of the force of one's hand, begin to move and will acquire speed (the greater, the bigger the force). This observation gave rise to Newton's second law.

But now the investigator—Newton again—leaves the everyday world and looks to the heavens to seek a clue to the 'harmony of the celestial spheres' which had stumped the ancient philosophers. What makes the planets move round the sun in the way they do and not otherwise?

The word 'harmony' suggests a system of order, the operation of some law governing the motion of the heavenly bodies. The matter is not one of 'spheres' naturally. But there must be a law governing the motion of the planets, and our earth too, about the sun and the motion of the satellites about their planets.

One might recall the ball moving along a swinging rope. The motion of the planets about the sun is indeed very much like the uniform motion of the ball, though it is slower and there is no rope. In short, if in one case a force is operative, it is reasonable to suppose that it is operative in another case too.

There is of course no way to perceive directly the action of the force governing the planetary motions. But the force is there. And Newton discovered it. We know that it is the force of the reciprocal attraction of bodies. Newton's genius lies in the fact that he perceived what is common between the motion of a ball and the orbital motion of a planet.

The important thing for us, however, is that the ball and rope was probably one of the first physical models. One gains an understanding of such a grandiose phenomenon of nature as planetary motion through the study of things on a much smaller scale—on the assumption of course that both are governed by similar laws.

The question arises as to whether this is justifiable everywhere and at all times. Is it right to extend the laws of one phenomenon to another one which is much larger or much smaller?

In Newton's time the answer was simple: since observation corroborates the development of some large-scale phenomenon that has been calculated on the basis of some small-scale one, or vice versa, everything holds true.

Roughly the same answer can be heard today as well. True, the approach is somewhat different. Newton believed, firstly, that the universe was unified and, secondly, that the laws governing its life both at man's level and in the big world of the planets and stars are the same.

From the vantage point of modern science, we are in full agreement with the first.

Now for the second, we cannot of course draw the conclusion that the inner workings of a phenomenon follow from similar outer phenomena.

A parrot repeats human words, but it would be naïve to suppose that while pronouncing a word the bird thinks.

The complexity of cognition lies in the fact that absolutely different laws are operative in the hierarchy of worlds of things, in the ultra-small, the ordinary, the ultrabig; and that there are great limitations to extending the laws of the ordinary world of things to other scales.

Physicists have been frustrated, when encountering the unruly entities of the ultrasmall, due to a misunderstanding of this important conclusion. Once convinced that microscopic particles refuse to fit into the framework of ordinary concepts, these physicists began to speak of anarchy, of a nature without laws. Yet this was not the case at all, as we shall see later on.

Model representation has played, and continues to play, an important role in the development of the natural sciences. Some of the greatest discoveries have been made with the aid of models constructed by human hands or, more often, existing only in the mind, since they cannot be built.

The ball supported by a rope was a very simple model. As time went on, more sophisticated models were developed. They became more and more complicated, bizarre. But exotic as these models might become, they have one thing in common. They are built out of the elements of the ordinary world about us, the world we see and feel.

This is a peculiarity of the human mind. The most fantastic abstractions and generalizations always proceed from actuality.

Not Everything Can be Modelled

From the end of last century on, the familiar model approach to the investigation of new things in nature was not always a success. For instance, the ether model. Its creators saw it the saviour of classical physics, which was unable to account for the remarkable constancy of the velocity of light.

Let us try to picture this ether. Something absolutely solid and just as absolutely transparent. Unbreakable glass? And yet, despite its hardness, the ether had to allow for all kinds of bodies moving freely. What is more, these bodies should be able to entrain the ether, building up something like a wind, a truly ethereal wind.

For a number of years physicists attempted to grasp these fantastic properties of the ether. But they failed. The ether proved to be a concoction with no roots in reality.

And the concept of ether was not the only rootless entity. Not a single model of classical physics for the atom was able to account for the mysterious release of energy by uranium, radium and other chemical elements—a radiation of energy that continues without interruption for many thousands and millions of years without any outside source.

Einstein's photon hypothesis was yet another blow to the old models. Though somewhat involved, it is still possible to fit into the classical model the concept of light as electromagnetic waves being propagated in all directions from their source.

We are accustomed to thinking of a wave as always being the motion of a material medium: the water for ocean waves, the air for sound waves. But electromagnetic waves are capable of propagation in an absolute void.

In this sense it is easier to picture light, as Newton did, as a stream of minute light particles. These particles are emitted by incandescent bodies, fly in all directions, and stimulate the optic nerve when they enter the eye, giving the sensation of light. There is now no

difficulty in imagining how these particles move in empty space.

But to picture light having wave and corpuscular properties at the same time, as Einstein did, is something we simply can't do.

In the model of the atom constructed by Bohr and Rutherford we have a conceivable picture. Minute particles—electrons—are revolving in definite orbits around a tiny nucleus. The dimensions of these orbits are tens of thousands of times greater than those of the electrons and nuclei.

With a little more imagination we can picture the atom as a sort of 'empty' structure, for we ourselves live in a planetary system where the dimensions of the 'electrons' (or planets) are thousands of times smaller than those of the orbits about the 'nucleus' (or sun).

However, just a few years later de Broglie completely confused the picture by stating that the electrons, nuclei and generally all material 'building blocks' of our world have the same duality as that introduced by Einstein for the photons; that is, that they possess at the same time properties of waves and corpuscles (particles). As a result, particles of matter, including atoms like those of light earlier, could no longer be visualized.

The Invisible, Untouchable World

Physicists were hard put. Before, they had trodden paths into new worlds, all the while sure that only the details would be different, not the essentials. But now they were in the shoes of explorers of old when anything could be expected, from monsters to half-beasts and half-humans.

There is no limit to the imaginings of a feverish mind.

Physicists had it even worse than those explorers, for the latter were always pleasantly disappointed to find normal beings and essentially the same earth, mountains and seas, only arranged differently. In the new world, scientists saw such bizarre things that no name was suggestive enough. Even the imagination did not suffice to picture this unusual new world of the atom.

But developing science demanded that some kind of conceptions be worked out, no matter how unconventional they might be. It was hard to construct quantum mechanics but it had to be done.

It surely would have been easier to build theories based on the visualizable models of the surrounding world. But what if the world of the ultrasmall was constructed differently? What if no such models could serve?

Well, if it is impossible to devise models that can be made into mental pictures, then we will have to work with models that cannot be pictured at all. Years passed, not many though, and these models became so 'unvisualizable', yet so dear to the physicists that no one wants to give them up. Which is too bad, because the time will come very soon—if we run ahead in our story a bit—when all these models will have to be jettisoned and replaced by still more unusual ones that will be even harder to grasp. That is how science develops.

Therein lies the greatness of the physicists of this century: they were able to reach their goal through a maze of abstractions and models far removed from everyday things, they succeeded in constructing a far-reaching theory of

the new world of the ultrasmall. What is more, on this basis, physicists achieved some of the greatest things in the entire history of civilization. They discovered the secret of nuclear energy, the jinni that had been bottled up for so long.

The atomic power industry and electronics would not be here today without the existence of quantum mechanics.

Difficult but Interesting

The unusual nature of quantum mechanical notions and the fact that these concepts cannot be visualized properly make the subject difficult to grasp. True, some of the fault lies in quantum mechanics itself. Not only because its range is continually expanding and its methods are constantly undergoing refinement; we know that it is always more difficult to write about something in the state of flux and development, and particularly such rapid development, than it is about firmly established theories. Not only this, but also because the physicists themselves are still, to this day, arguing about the very meaning of quantum mechanics, about the specific aspects of the minute world that it describes.

We have now entered the space age, where again physics is called upon to pave the way. The physics of cosmic space differs radically from 'terrestrial' physics in that the world of the ultrasmall is of prime importance.

The ancient idea of the great and the small meeting finds its confirmation in outer space. Enormous stars and minute atoms not only converge but exist as an integral unit.

It is almost impossible to write popularly about science without resorting to some kind

of visual representations. And so with quantum mechanics we shall try to find analogies, if not models, in nature. However, such analogies are in no way exact or profound. They simply help us to get a general grasp of things.

For instance, as we shall see, the phrase 'electrons revolve around an atomic nucleus' hardly have more meaning to us than the words 'snow is something white, rather like salt and falls from the sky' have for the inhabitants of tropical Africa. The motion of an electron in an atom and the essence of the electron as such is immeasurably more complicated than what we know about them today and the way we picture them. And not only today, tomorrow and a thousand years hence!

Indeed, the development of quantum mechanics is added prove of the limitless diversity, the inexhaustibility of the properties of the electron. And everything else as well.

We today still have rather fragmentary knowledge of the world about us. We are only beginning to penetrate into the earth's crust, into the oceans, the atmosphere. We have only just started to understand the life of the fields, the forests, the mountains, the rivers and the deserts.

If that is so, how can we expect to know as much about the world of atoms, atomic nuclei and elementary particles, which are still more difficult to observe. There is exploration ahead in this science for hundreds and thousands of years. As yet we are only at the source of a mighty river of knowledge.

Even so, what amazing things are revealed to the explorer of this recently discovered world. What inspiring, truly fantastic horizons does

this new science open up for technology, industry, agriculture and medicine. Nuclear power stations, radioactive isotopes, solar batteries, to name a few. We are on the threshold of controlled thermonuclear reactions and we are penetrating into outer space. All these great attainments of the bright present and the dazzling future were born in our century out of a small seed thrown, sixty years ago, into the fertile soil of scientific knowledge by Max Planck and, since, carefully cultivated by a whole galaxy of brilliant scientists.

The First Steps of the New Theory

Heat and Light

It's nice, on a cold winter evening, to sit near a hot stove and listen to the sputtering flames inside and feel the warmth of the fire. But why warmth? Why is it warm near a stove? Without even seeing the fire inside, one can feel the heat at some distance away.

A stove emits some kind of invisible rays that give the sensation of heat. These rays are called heat rays, or infrared rays.

A little careful observing will show us that thermal radiation is quite a common thing in nature. Both heat and light are emitted by a candle, a large fire, and our enormous sun. Even the fantastically distant stars send heat rays to the earth.

If a heated body glows, it definitely is emitting heat rays as well. The emission of light and heat is actually one process. That is why scientists gave the name thermal radiation to all emissions of a body that appear to be due to a heating process—both the emission of light and the thermal radiation proper.

Last century, physicists had already discovered the basic laws of thermal radiation. They are familiar to all of us. Let us recall two laws.

First, the more a body is heated, the brighter it glows. The quantity of radiation emitted per second varies drastically with change of temperature of the body. If the temperature is increased three times, the radiation will increase almost one hundredfold.

Second, the colour of the emission changes with an increase in temperature. Observe a piece of iron pipe under the flame of a torch. At first it is quite dark, but then a faint crimson tinge appears, this turns red, then orange and yellow. And finally the heated metal begins to emit a white light.

An experienced steelworker can gauge the temperature of an incandescent pipe quite accurately by the colour of luminescence. He will say that a faint crimson tinge means a temperature of about 500°C, yellow is about 800°C, and bright white is over 1,000°C.

Physicists are not satisfied with this rough qualitative description, they want exact figures. To a physicist, 'the day is cold' means about as much as 'he had a big face'. What one needs is the peculiar features, the nose, the lips, the forehead.

Physicists had encountered a great diversity of bodies and conditions in which thermal radiation is emitted. But this diversity of conditions did not satisfy them in the least. They wanted some kind of 'standard' body, a criterion to be used as a basis for establishing the laws of radiation of heated bodies. Then the emission of light by other bodies could be regarded as deviations from this 'standard'. Picture a de-

scription like this: "The nose of the man was longer than the standard nose, the forehead was narrower, the jaw more extended, the eyes somewhat greener and somewhat smaller than normal." Rather strange to us, but the physicist would be delighted. Here's why.

Blacker than Black

Take a number of objects of the same colour, as close as possible. Now examine them closely and try to see how they differ in colour.

A close examination will show that there are differences. One has a faint tinge, another has a deep, rich colour. This difference is due to the fact that a certain amount of light falling on the body is absorbed and a certain amount is reflected. Naturally, the relationships of these two amounts can vary over a tremendous range. To take two extreme cases, a shiny metallic surface and a piece of black velvet. The metal reflects almost all the light that falls on it, while the velvet absorbs most of the light and hardly reflects any.

Magicians make good use of this property of velvet, for if an object does not reflect much light, it is practically invisible. On the stage, a box covered with black velvet on a black background goes quite unnoticed, and the magician can go through all kinds of tricks with handkerchiefs, pigeons and even himself appearing and disappearing.

Physicists also found this property of black bodies very valuable. In the search for a standard body, they decided on the black body. A black body absorbs the most radiation and, hence,

is heated by this radiation to a higher temperature than all other bodies.

Conversely, when a black body is heated to a high temperature and becomes a source of light, it radiates more intensely at the given temperature than any other bodies. This, then, is a very convenient radiator for establishing the quantitative laws of thermal radiation.

However, it was found that black bodies themselves emit radiation in different ways. For example, soot may be blacker or lighter than black velvet, depending on the fuel it comes from. And velvet too can differ. These differences are not great, but it would be good to get rid of them.

Then physicists thought up the 'blackest' body of all, a box. A very special kind of box to hold thermal radiation. It was ribbed with inner walls covered with soot. A ray of light enters through a tiny aperture and never gets out again, caught for all time. The physicist says that this box absorbs all the radiant energy that enters it.

And now let us make the box a source of light; actually, this is what it was intended for. When heated sufficiently, the walls become incandescent and begin to emit visible light. As we have already said, for a given temperature the thermal and light radiation of such a box will be greater than for any other bodies, which are then called gray to distinguish them from our box.

All the laws of thermal radiation were established precisely for the 'very blackest' boxes, which were given the generic name 'black bodies'. With slight alterations, these laws apply also to the gray bodies.

Let us now redefine our laws more exactly, in the language of physics.

The first states that the radiating capacity of a black body, that is the energy it emits in the form of light and heat every second, is proportional to the fourth power of its absolute temperature. * This law was discovered at the end of last century by the German scientists Stefan and Boltzmann.

The second law states that as the temperature of a black body increases, the wavelength corresponding to maximum brightness of the light emitted by it must become shorter, and is shifted towards the violet region of the spectrum. This was called Wien's displacement law in honour of the Austrian physicist W. Wien.

Physicists now had at their disposal two universal laws of thermal radiation that could be applied to all bodies without exception. The first gives a correct description of increasing brightness of luminescence as a body is heated. It might appear that Wien's law is in poor agreement with observations, since as the temperature increases, the body emits more and more white light. White, not violet.

But let us take a closer look. The Wien law only speaks of colour corresponding to maximum brightness of light radiation, and nothing else. It is tacitly assumed that in addition to this radiation there remain the radiations of longer wavelengths (i.e., of a different colour) that had started earlier at a lower temperature.

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* Absolute temperature is reckoned from 273 degrees below 0 degrees Celsius.

When a body is heated, its radiation widens the spectral range, opening up fresh regions of the spectrum. As a result, if the temperature gets high enough, we have a complete visible emission spectrum.

This might be compared to an orchestra in which more and more instruments come in with higher and higher notes until the whole ensemble sounds in one mighty accord, from the deep 'red' base of the trombones to the highest shrill 'violet' of the piccolos. And white light is the whole spectrum at once. Wien's law holds true. But nature dealt a blow to the investigators of thermal radiation from quite a different angle.

The Ultraviolet Catastrophe

Physicists have a penchant for universal laws. As soon as it is discovered that one and the same phenomenon is described, in various aspects, by several laws, an attempt is immediately made to combine them into a single general law encompassing all aspects at once.

Such an attempt was made, with respect to the laws of thermal radiation, by the English physicists Rayleigh and Jeans. The unified law which they obtained stated that the intensity of radiation emitted by a hot body is directly proportional to the absolute temperature and inversely proportional to the square of the wavelength of the emitted light.

This law appeared to be in good agreement with experimental findings. But it was suddenly discovered that the agreement was good only for the long-wave portion of the visible spectrum, the green, yellow and red. The law broke down

as the blue, violet and ultraviolet rays were approached.

From the Rayleigh-Jeans law it followed that the shorter the wavelength, the greater should be the intensity of thermal radiation. Experiment failed to confirm this. What is more, a very unpleasant thing was that as we move to shorter and shorter wavelengths the radiation intensity was supposed to increase without bound!

Of course, this doesn't occur. There can never be an unbounded growth in wave intensity. If a physical law leads to 'unboundedness', it is doomed. Nature has large things, very large, even unimaginably large things, but there is nothing without bounds, except the universe itself.

This curious situation that arose in the theory of radiation became known as the 'ultraviolet catastrophe'. That was at the end of last century. At that time, nobody could even imagine that it was not simply a catastrophe for one, rather special, law. It was the collapse of the entire theory that gave birth to the law—the catastrophe of classical physics!

Classical Physics at an Impasse

There were physicists in those days who did not regard this radiation-theory obstacle in the path of classical physics as significant. But any hindrance is a grave matter, for everything in the theory is interrelated. If some point is false, we cannot rely on the description it gives of other phenomena. If the theory is not able to overcome a little barrier, what hope is there for big barriers?

Physicists made heroic attempts to surmount the difficulties of radiation theory. Today, these attempts seem logically inconsistent. Yet what can one expect? When a theory gets into a hot spot, it is like a cat in a burning house with one way out—into the river. The cat races from corner to corner, but it never thinks to jump into the water, for that would be against all the cat's instincts.

Something similar happens to scientists who are caught 'burning' in the house they have worked all their lives. The house which is so dear to them and to which they are so accustomed. They try to put the fire out, but they can't conceive of running away and leaving it.

However, it became clear to the more acute scientists that classical physics had reached an impasse. And the theory of thermal radiation was not the only blind alley. Those same years saw the ether theory collapse too.

The breakdown was so rapid that many were in complete despair. What was there left to do?

If the facts don't fit the theory, so much the worse for the facts. Nature does not want to obey any laws. Nature is unknowable! That is how those with weaker nerves reacted.

The reaction of the materialist-thinking scientists was different. If the facts cannot be explained by the theory, so much the worse for the theory. It will have to be reconstructed on a new basis, and immediately.

History once again demonstrated that great necessity gives birth to great men. The way out of this cul-de-sac of classical physics with its immutable dogmas was found by Max Planck, who in 1900 introduced the concept of quanta, and by Albert Einstein, who in 1905 advanced the theory of relativity.

The Way out

What was Planck's discovery?

At first glance it is hard to call it a discovery. There were two laws dealing with the thermal radiation of hot bodies. Separately, they held true very well, but when joined into a single law it confronted the 'ultraviolet catastrophe'. Something like two men meeting with just about the same way of thinking; after a little discussion they come up with absolutely 'mad' ideas.

Planck at that time was over forty. For many years he had been studying thermal radiation. Right before his eyes the theory had come to an impasse; like his colleagues, he was seeking a way out. He checked the entire chain of reasoning and was finally convinced that there was no mistake. Planck then went further and in a different direction.

In later years he recalled how he had never worked as hard and with as much youthful energy and inspiration as in those years at the turn of the century. The most improbable things began to appear to him quite possible, and with the persistence of the fanatic, Planck went through one version of the theory after another.

At first he was guided by a rather simple idea. Rayleigh and Jeans had combined the two laws of thermal radiation into one and had obtained an absurd result for short wavelengths. Maybe it is possible to link up these laws with Wien's law in a different way and get something reasonable.

For his experimental material, Planck tried to find some general formula that did not contradict the material. After some search he found such a formula. It was rather involved. It contained expressions that do not have obvious

physical meaning—just an accidental combination of unrelated quantities. But strangely enough, this concocted formula was in excellent agreement with experiment.

What is more, from it Planck was able to derive the Stefan-Boltzmann law and the Wien law. And taken as a whole, the formula did not have any 'infinities'. A correct formula, the physicist would say.

Victory? A way out? Not exactly. Planck, a real scientist, was inclined to doubt.

Hitting the keys of a piano twenty times at random might yield a tune, but where is the proof that it must produce a melody? The formula had to be deduced from something. Science does not recognize the rule whereby the winner is not critisized. On the contrary, he always is, and very fundamentally. Until the winner can prove every step in his competition with nature, victory is not recorded.

And it is here that Planck failed. The formula did not want to be derived from the laws of classical physics. Yet, it fit the experimental data in miraculous fashion.

That was the dramatic situation in which Planck found himself. Would he take the view of classical theory against the facts or would he stand by the facts and fight the old theory? Planck took the side of the facts.

Quanta of Energy

What was it in classical physics that made it impossible to derive Planck's formula? Nothing less than one of its most fundamental premises: the statement, so common and unshakable to

the physicists of those days, that energy is continuous.

At first glance this would seem to contradict the spirit of classical physics, which from the very start recognized the discontinuity of things as an underlying principle. It appeared quite obvious. If we have empty space in the world, all objects have to be separated from one another and have boundaries. Objects do not pass one into another in continuous fashion, each one ends at some point.

Maybe the situation is different inside things. No, there doesn't seem to be any continuity here either. Classical physics, at the end of the 19th century, was forced to recognize the existence of molecules and of empty space between them. The molecules had clear-cut boundaries, and only the void between was continuous.

Incidentally, molecules somehow managed to interact through this emptiness. Since the time of Faraday, classical physics had been trying to account for this interaction by the existence of some sort of intermediate medium, via which the mutual action effects of the molecules were conveyed.

What about energy, though? It was held that when molecules collided, energy was exchanged in every imaginable quantity. This exchange followed exactly the laws of billiard balls. A moving molecule hits a stationary one, gives up part of its kinetic energy, and the two molecules then move off in different directions. In a head-on collision, the incident molecule can even come to a stop; then the struck molecule will fly off with the speed of the first one. Molecules are constantly exchanging energy.

Another form of energy was found, one not

obviously connected with molecular motion—the energy of wave motion. Since Maxwell proved that light is electromagnetic waves, the energy of light radiation (of thermal origin, for instance) must follow the laws obeyed by all waves.

Again, this energy is continuous. It is propagated together with the moving wave flowing like water. Any given quantity of energy is consumed continuously in the same way that water continuously and indivisibly fills a vessel.

When we cut off a piece of butter, we do not think about the continuity of the piece. We assume that it can be made as small as we please. When the concept of molecules was introduced into science, it became clear that there was no such thing as a piece of butter smaller than a molecule of butter.

Now with regard to energy, there was no such notion of discreteness. It appeared that the atomistic structure of matter did not demand that energy be composed of 'pieces'.

It was enough to look around us to see that that was so. The light from a candle filled a room with an even flow of radiant energy, just as the sun kept up an uninterrupted stream of light. Or take the smooth build-up of speed (and with it, energy) of a locomotive moving downhill, of a falling stone.

Imagine for a moment that energy is acquired and given up in little portions. One calls to mind the jerky movies of years ago. One pictures the candle flaring up and dying down, the sun shining in bursts, as it were, a flash of radiant energy, and then a lull until the next flash. The train moving down a slope in jerks, the stone bumping along through the air in its plunge to earth.

"Sheer nonsense!" was the answer Planck most likely got from his first suggestion that the energy of radiation (like matter itself) is atomistic and that it is released and acquired not continuously but in small portions, quanta, as Planck called them, from the Latin 'quantum' meaning quantity. If he had only known the quality that would eventually grow out of such quantity!

For Planck's formula, quanta were vitally important. Without them, it would have failed miserably and would have gone to the dusty archives of science along with so many others that have found no substantiation.

These quanta of energy served as a firm foundation for Planck's formula. But the foundation itself rested on practically nothing since there was no place for it in classical physics. That is exactly what troubled the cautious Planck. It is no easy matter to give up a lifetime of habit.

The Elusive Quanta

A quantum of light is an extremely small portion of energy. The most minute particle of dust has thousands of millions of atoms. The radiant energy released by a tiny glow-worm contains thousands of millions of quanta.

Now we come to the magnitude of these separate portions of energy. Planck made the extremely important discovery that these portions differ for different types of radiation. The shorter the wavelength of light, that is the higher its frequency (in other words, the 'more violet' it is), the larger the portion of energy.

Mathematically, this is expressed by means of the well-known Planck relation between the

frequency and the energy of a quantum:

$$E=h\nu$$

Here, E is the energy of the quantum; ν is the frequency of the quantum; h is a proportionality factor which turned out to be the same for all types of energy that we know. It is known as 'Planck's constant' or the 'quantum of action'. The value of this number is just as great to physics as its magnitude is small: 6×10^{-27} erg per second!

It is this insignificant magnitude of the quantum that makes the light of a candle or the sun appear to us to burn with a constant glow. To illustrate, let us calculate the number of quanta radiated by a 25-watt electric light bulb per second. Taking the emitted light to be yellow, we find by Planck's relationship 6×10^{19}, which is 60 million million million portions of energy per second. All of that is radiated by a small 25-watt bulb every second!

Quite obviously, the human eye is not sensitive to such magnitudes of energy. Yet this is not so. The eye is an extremely sensitive instrument, as was convincingly demonstrated by the experiments of the Soviet physicist S. Vavilov. An observer was kept in the dark for a certain time (to increase the sensitivity of the eye) and then an exceptionally weak source of light that yielded just a few quanta per second was switched on. The eye recorded them almost as separate entities!

The point is not the magnitude of the quanta but the very high rate at which they follow one another. We have already seen that even a small lamp emits millions upon millions every second. Now the human eye, like any other instrument,

operates with a time lag. It is not able to record events that proceed in rapid succession. This inertia-like property of the eye is what makes moving pictures possible. We see the screen as a continuous sequence of events, although we know that the pictures are actually in the form of separate frames.

Energy quanta emitted by sources of light follow one another much more rapidly, and so the human eye sees light as one continuous flow.

Vavilov conducted his experiments in the 1930's, when Planck's notion of quanta was generally recognized. Planck himself was not able to prove his discovery by direct experiment.

The fact that a formula is corroborated by experiment but does not follow from theory always appears at first somewhat dubious. In this case, all the more so since the formula was obtained from reasoning that ran very much against the grain of accepted thought. That was why there was not much enthusiasm in scientific circles when Planck delivered his communication at the Berlin Academy of Sciences. Scientists are human beings, too, and they require time to digest something so out of the ordinary.

Planck himself was fully aware of the boldness of his attack on classical physics and was eager to justify it. But of course he could never imagine the tremendous developments that revolutionized the whole of physics just a few years later.

The first years of the twentieth century, 1901, 1902, 1903, 1904, went by with hardly any attention paid to the theory of quanta. The number of papers that appeared could be counted on one's fingers.

An Unaccountable Phenomenon

But then in 1905, a totally unknown member of the Swiss Patent Office, Albert Einstein, published his theory of the photoelectric effect in metals in the German journal "Physikalische Rundschau".

At the time that Einstein took up this study, the effect was well on in years. It had been discovered in 1872 by A. Stoletov, professor of Moscow University. Later on it was studied by the German physicists Hertz and Lenard.

Stoletov had pumped the air out of a flask, put two metallic plates inside and attached them to the poles of an electric battery. Naturally, there was no current through the airless space. But when the light of a mercury lamp was made to fall on one of the plates, current immediately began to flow in the electric circuit. When the light was turned off, the current stopped.

Stoletov drew the proper conclusion, that current carriers (electrons) had appeared in the flask and that they originated only when the plate was illuminated.

It was quite obvious that these electrons were ejected from the illuminated metal much like molecules jump into the air from the surface of heated liquid. However, the words 'much like' really mean 'quite differently from'; the ejection of electrons from metal was fundamentally different and, what is more, was of an unknown nature.

To begin with, light is an electromagnetic wave. It is difficult to imagine how a wave can knock electrons out of metal. There is no collision here of energetic molecules, as a result of which one of them is ejected from the surface of a liquid.

Another interesting circumstance was noted. For each metal studied, there appeared to be a certain limiting wavelength of incident light. When this wavelength was exceeded, the electrons in the flask disappeared at once and the current ceased to flow no matter how strong the light was.

This was altogether strange. It was clear that electrons are ejected from the metal because the light in some way conveys energy to them. The brighter the illumination, the stronger the current. The metal receives more energy and larger quantities of electrons can be knocked out.

But no matter what the wavelength of the light, the metal should be receiving energy all the same. True, with increasing wavelength the energy diminishes and fewer electrons are ejected from the metal, but still there should be some kind of current. Yet experiment showed no current at all. One would think the electrons ceased to accept the radiant energy.

How was one to figure out why electrons were so particular about the energy food they were given? That was something that the physicists just could not grasp.

Photons

Einstein regarded the photoelectric effect from a different angle. He attempted to picture the actual process of the ejection of an electron from a metal by light.

In normal conditions, there is no cloud of electrons hovering over the metal. Which would suggest that the electrons are bound to the metal by some kind of force. To knock them out of the metal, a little energy is needed. In Stoletov's

experiments this energy was supplied by light waves.

But a light wave has a definite wavelength, something on the order of a fraction of a micron, and its energy is, as it were, concentrated in the minute volume occupied by an electron. This means that in the photoeffect a light wave behaves like a tiny 'particle'. It strikes an electron and dislodges it from the metal.

This must obviously be a particle of light; as Newton would say, a corpuscle, because Newton regarded light not as waves but as streams of particles. Then what would the energy be of such a particle? Calculations show that it would be very small. Then why not suppose that it would be exactly equal to the quantum that Planck had conjured up five years before?

So Einstein said that light is simply a stream of quanta of energy, all the quanta of a single wavelength being exactly the same, which is to say that the quanta carry identical portions of energy. Later, these quanta of light energy were given the name photon.

The explanation now was complete. A photon carrying a small portion of energy strikes an electron with sufficient force to knock it out of the metal.

On the other hand, obviously, if the photon energy is insufficient to disrupt the electron bonds in the metal, the electrons will not be knocked out and there will be no current. According to Planck's formula, the energy of a quantum is determined by its frequency, and the greater the wavelength of the light, the lower the frequency. Hence it is quite obvious that the photoelectric effect has definite limits. It is simply this: if the wavelength of the light is

too large, the photons do not have energy enough to dislodge electrons from the metal.

What is more, it doesn't make any difference how strong the light is, whether a thousand or only two photons strike the metal and bombard its electrons: the latter are indifferent. The situation changes if the photons have sufficient energy. In this case, the brighter the light, the more photons enter the metal every second, and the greater the number of electrons ejected, thus producing a stronger current.

Thus, an explanation has been found. But, like the Planck hypothesis, it undermines the foundations of classical physics, where light is considered to be electromagnetic waves and under no circumstances these new-fangled photons. Einstein's theory again started up the two-century argument over the essence of light.

What is Light?

Actually, there was never any let up in the argument. The problem arose at the dawn of classical physics and lived a tempestuous life. The dilemma was: what is light, waves or particles?

Both viewpoints appeared in physics at about the same time. Bodies shine by ejecting streams of light particles, corpuscles, said Newton. Bodies shine by pulsating and forming waves in the surrounding ether, said Newton's contemporary, Huygens, of Holland.

Each theory had its adherents, and they clashed from the start. It was a fierce struggle that went on for over a hundred years, first one side winning and then the other.

Finally, at the beginning of the nineteenth century the experiments of Young, Fresnel and Fraunhofer resulted in what would have seemed a decisive victory for the wave theory of light. The newly discovered phenomena of interference, diffraction and polarization of light were in excellent accord with Huygens' theory and quite incomprehensible from Newton's viewpoint.

Optics began to develop. Brilliant optical theories were developed and complex optical instruments were constructed. Finally, Maxwell completed the structure of optics by proving the electromagnetic nature of light waves. The triumph of the wave theory was complete and indisputable.

But less than fifty years passed and the corpuscular theory of light was again revived. The photoelectric effect which the wave theory had failed to explain—what an annoying blemish on an otherwise perfect structure!—was accounted for in amazing fashion by the opposing theory.

The century-old argument again flamed up. But now the fight was on a new level. Both adversaries were tired out and ready for a compromise of some kind. Gradually it dawned on physicists that the amazing and inevitable view had to be that light is at the same time both waves and particles!

But why is it that light never manifests itself completely in this twofold manner? Sometimes it appears only as particles, yet at other times it is only in the form of waves. We shall take that important question up later on.

The second question that came with Einstein's theory was not simple either. It appeared that

in the photoelectric effect the electrons did not react to just any portion of energy offered them. The portion of energy had to be of a very definite magnitude or greater, otherwise the light energy found no response.

It also turned out that an electron which is not bound by any forces to neighbouring ones ceases to be particular and responds to all kinds of energy packets. But if the electron should find itself in a metal, it gets moody and demands specific portions of energy again.

Why this is was explained some twenty years later.

The Visiting Cards of Atoms

Meanwhile, a young Danish physicist, Niels Bohr, tried to apply the new quantum concepts to the respectable science of spectroscopy. By the twentieth century, hundreds of papers had appeared dealing with spectroscopy. Spectral analysis was moving ahead at quite a pace doing great service in chemistry, astronomy, metallurgy and other sciences.

Credit for the discovery of spectra goes to the diversified genius of Newton. But spectral analysis made its appearance only a century ago. In 1859, the prominent German chemist Bunsen repeated Newton's old experiment by placing a glass prism in the pathway of the sun's rays and decomposing the light into a spectrum. In Bunsen's experiment, the role of the sun was played by a burning rag dipped in a salt solution. Newton had found that the ray of sunlight is expanded into a band of many colours. Bunsen didn't see any band at all. When the rag had table salt (sodium chloride) on it,

the spectrum exhibited only a few narrow lines, nothing else. One of the lines was a bright yellow.

Bunsen got another well-known German scientist, Kirchhoff, interested in this fact. Both of them correctly concluded that the role of the glass prism consisted only in sorting the incident rays of light into their wavelengths. The extended band of the solar spectrum indicated that all the wavelengths of visible light were present. The yellow line, which appeared when the light source was a burning rag, indicated that the spectrum of table salt had a single specific wavelength.

The formula of sodium chloride is NaCl. To which element (sodium or chlorine) did the yellow line belong? This could be checked very simply. The sodium could be replaced by hydrogen, giving us hydrogen chloride, HCl, which, when dissolved in water, yields hydrochloric acid. The rag was dipped in hydrochloric acid and placed in the flame of a Bunsen burner and the spectrum was taken. The yellow line had disappeared without a trace, which meant that it belonged to sodium.

This was verified once again. The sodium was retained, and the chlorine was replaced (caustic soda, NaOH). The familiar line appeared in the spectrum immediately. There was no longer any doubt. No matter what the substance in which sodium appeared, it made its whereabouts known by the bright yellow spectral line, its visiting card.

Later, it was found that sodium is no exception in this respect. Every chemical element has its own characteristic spectrum. As a rule, some of the spectra were much more complicated than that of sodium and consisted at times of a very

large number of lines. But no matter what the compound or substance the element appeared in, its spectrum was always distinct, like the photograph of a person.

One might look for a person in a crowd by checking the identification card of each one, like chemists do when looking for elements in rock specimens using chemical methods of analysis. But an easier way is to have his photograph. Which is precisely how the search is done with the aid of spectral analysis. And the elements are found in places where 'looking over identification cards' would be out of the question—on the sun, in distant stars, in the inferno of blast furnaces and in plasma.

All that is needed is the photographs of all the participants. Today there are over a hundred chemical elements, and nearly all of them have been classified according to their characteristic spectra.

Why do Bodies Emit Light?

The successes of spectral analysis were colossal, but there was a fundamental flaw. The edifice of spectroscopy was erected on the foundation of the theory of thermal radiation and bore all the traces of the basic shortcoming of this theory. The basic weakness lay in its answer to the question: Why do bodies begin to emit light when heated?

How is this light emitted? Obviously, by the component parts of the bodies—atoms and molecules. Increasing temperatures make the molecules move faster. Mutual collisions are more violent and more frequent, and the molecules vibrate so fast that they begin to emit light.

That was the view of the old physics. But then why do not bodies luminesce at room temperature, since the molecules are still in motion? No explanation was then forthcoming.

When, in 1898, the English scientist Thomson created the first model of the atom, the mystery of luminescence seemed about to be solved. In this model, atoms were clouds of positive charge within which floated negative electrons in quantities sufficient to balance the charge. The electrons were attracted by the positive clouds and retarded in their motion.

But according to classical physics, charged particles have to emit electromagnetic radiation when they are decelerated. Apparently, that radiation is the light emitted when bodies are heated. At first glance, the explanation was quite convincing. The more a body is heated, the faster the electrons move in the atoms and the greater the deceleration due to the attraction of the clouds of positive charge, and hence the more intense the radiation.

That could be the case if electrons did not expend energy when radiating. But when electrons radiate light, they must decelerate with extreme rapidity. In just the most minute fraction of a second they would have bogged down in the positive clouds like raisins in pudding.

Something was wrong. Several years later it became evident that the Thomson model of the atoms would not work in other respects as well. Too many questions remained unanswered. And then why don't the electrons simply merge with the positive cloud and neutralize their charge? The few answers that are obtainable from this model in most cases come into sharp conflict with experiment.

In 1911, the eminent English physicist Ernest Rutherford proposed a new model of the atom. Rutherford bombarded atoms of various substances with the newly discovered alpha rays of radioactive substances. It was already known that these rays consist of positively charged particles.

Studying the scattering of alpha particles by atoms, Rutherford was forced to a conclusion with far-reaching consequences. The alpha particles were scattered as if they were repulsed not by the entire positive cloud of the Thomson atom, but by a very small portion of the atom concentrated somewhere at the centre. The entire positive charge of the atom appeared to be concentrated in this tiny central part.

Rutherford called this part of the atom the core (nucleus). Then where are the electrons? The old view that the electrons were bound to the positive charge in the atom by the electric forces of attraction was not in doubt. But since the electrons exist at a certain distance from the core, there must be some force that counterbalances the electric force of mutual attraction of electrons and nucleus.

It was obvious that this force had to be operative all the time. Atoms exist for a sufficiently long time, and so the countering force would obviously have to be just as constant as the force of electrical attraction between the electrons and the nucleus.

It seemed reasonable to think that this was a centrifugal force. It appears if electrons revolve about the atomic core. It could be calculated whether the force is sufficient to keep the electrons from falling into the nucleus. Calculations showed that it is quite sufficient if the electrons revolving about the nucleus move at speeds of

many tens of thousands of kilometres per second and at a distance from the nucleus of the order of hundred millionths of a centimetre.

This was the Rutherford model of the atom. A ball swinging round at the end of a rope had indirectly suggested to Newton the idea of planetary gravitation; this same idea now led Rutherford to the ingenious and perfectly correct (as the future has shown) concept of a planetary structure of the atom.

Now we can return to the problem of why bodies emit light and seek the answer in the new model of the atom. The motion of electrons about the nucleus is accelerated motion (the electrons move along closed curves). Hence, there must be electromagnetic radiation. The classical laws are equally applicable to the Thomson model and the Rutherford model of the atom. But, unfortunately, the success is also the same. In radiating light, the electron uses up its energy. In doing so, it slows down in millionths of a second and must inevitably fall onto the nucleus, just like a satellite decelerated in the earth's atmosphere falls to earth. The fate of the electron should be the same as that of the satellite. An atom, under such conditions, would very soon cease to exist.

But atoms live on. Electrons should not be giving up energy and should not emit light. But bodies do emit light when heated!

The Biography of the Atom Written by Niels Bohr

Classical physics was again at an impasse. And a worse one than might be supposed. It was not able to account for the luminescence of

heated bodies, and it could not explain the existence of spectra.

You remember the rag with the sodium chloride solution. The spectrum of this salt consists of only one yellow line, which means that the radiation of its atoms consists of only one wavelength.

Even if we assume that this line is emitted by an electron decelerated in the atom, we are immediately confronted by another difficulty. The laws of classical physics state that such an electron should emit not one line but a whole spectrum of lines with all wavelengths, and with no discontinuities in the spectrum. The spectrum of an electron should not differ from the spectrum of the sun. Yet we have only one yellow line!

Bohr realized that something was wrong. But what? Maybe the Rutherford model of the atom was to blame? No, it was too early to reject this model. And Bohr's teacher, Ernest Rutherford, was of the same opinion. It was thought an attempt should be made to modify and improve the model so that an electron in it could revolve about the nucleus and emit light and yet not fall onto the nucleus.

The year was 1912. Fresh in the memories of all physicists was the sensation that Einstein had created with his photons. And only three years before, it was Einstein again who completed his theory of relativity—another sensation. Naturally, all these attacks on classical physics could not but stir up the young physicists and add boldness to their mode of thinking.

Bohr continued to mull over the problem and at last got an idea. Why should an electron in an atom emit light continuously? Because it

is always moving at an accelerated rate? Let's reject that and say that an electron in an atom need not give off light even when in accelerated motion.

And how is this possible? The electron has to move along specific paths about the nucleus, in orbits, and not just any way. If the electron does not emit light, it can live in the atom as long as it likes.

But there was no way in which classical physics could countenance such a situation. What is more, it didn't follow from any other theory. Bohr was not able to prove it. And so he modestly called it a postulate. Bohr, incidentally, was never able to prove it within the framework of his theory. The proof came some ten years later and was quite unexpected. That we'll discuss later on. But how many possible orbits are there in which an electron can move without emitting light? Bohr's calculations show that the number is great, maybe infinitely great. What's the distinguishing feature? The mean distance from the nucleus: there are close orbits and distant orbits. Yet it is not a question of distance, but of the energy which the electron possesses in its orbit. Which is understandable, because the closer an electron is to the nucleus, the faster it has to move to keep from falling onto the nucleus. The reverse is true of a more distant electron, which is not so strongly attracted to the nucleus, and hence can move more slowly.

The conclusion, then, is that the pathways (orbits) of electrons differ as to electron energy. As long as an electron stays in its orbit, there is no emission of light.

Bohr at this point advanced a second postulate. Let us suppose an electron in orbit suddenly

jumps to another orbit of less energy. Where has the excess energy gone? Energy cannot simply vanish away into nothing.

Seek it outside the atom, says Bohr.

This energy is ejected from the atom in the form of a quantum, that same quantum of light energy which Einstein called a photon.

An electron that has emitted a photon takes up a different orbit and does not emit light any more. The photon was ejected during the minute fraction of time when it jumped from one orbit to the other.

Meanwhile the photon was making its way through the other atoms and finally got out of the substance. It can enter our eye, it can be passed through a glass prism in a spectroscope and photographed. The energy contained in photons is transformed many times before we see its actual image as a black line on a photographic plate.

This line has a lot to say for itself. By measuring its position on the plate we can find the wavelength of the photon and its frequency. Then we take the Planck relationship between frequency and energy of photons and determine the energy of the photon. This energy comes out as the exact difference in energy between the old and new orbits in the atom. The blackness on the plate at the site of this spectral line indicates the number of photons there: the more there are, the blacker the line. The more photons, the brighter the body that has emitted them.

What a simple and elegant explanation of spectra.

All the atoms of a certain substance are exactly alike. Hence, the electrons all exist under the same conditions. And so the photons emitted

during jumps between two orbits are all the same. All the transitions that electrons make between two orbits yield, in the final analysis, a single unique spectral line.

We have already mentioned that there are quite a few such old and new orbits. An electron can reside in any one of them, in turn.

Every jump from a higher-energy orbit to one of lower energy is accompanied by the birth of a photon. But since there is a difference of energy between different orbits, the photons will have different energy and frequency. A photographic plate will then exhibit a series of narrow spectral lines. This is exactly what the spectrum of gaseous hydrogen looks like. It has several tens of lines with different wavelengths.

Generally speaking, such a simple spectrum as that of sodium consisting of only one line is a rarity. Spectra usually have many tens of lines and frequently even thousands of lines. The spectral patterns of some chemical compounds are so intricate that there doesn't seem to be any hope of disentangling them. But there are laws to go by which make the task easy.

Before Bohr's theory, physicists racked their brains in attempts to decipher some of the complicated spectra. And when Bohr proved that the spectrum is the biography of the atom, more precisely, of the atomic electrons, the job was greatly simplified. All one had to do was to combine the various electron orbits in an atom until he obtained the observed lines of the spectrum.

And conversely, by examining a spectrum, one can draw all manner of conclusions about the conditions under which atomic electrons exist. This is very important. Actually, just

about all that we know about the electron shells of atoms has been acquired through a painstaking analysis of their spectra.

From Where do We Reckon the Energy?

Now that Bohr has explained how an atom emits light, let us ask WHY. Why do bodies begin to emit light only at a high temperature and why do they cease to emit light at room temperature?

Before answering this question we shall have to digress a bit. The very convincing picture of the atom which we have just drawn will have to be turned upside down. Not that there is something wrong with it. No! It is simply the sequence of electron orbits that has to be reversed.

We considered the close orbits to be the most energetic ones, whence it followed that a photon was emitted when an electron jumped to an outer orbit from the nucleus. Actually, it is just the other way around.

Let us try to picture this business by digging a hole in the ground. Put a ball at the bottom of the hole and put another one on the ground near the hole. Which of the two balls has the greater energy?

A knowledgeable person will immediately say: "The question is not clear. First, what energy are you talking about, potential or kinetic? Second, from what level do you reckon the potential energy? If the level of the earth is taken, then the potential energy of the ball on the ground may be taken as zero, then the ball in the hole will have a potential energy less than zero, that

is, negative energy. But if we reckon the potential energy from the bottom of the hole, then the ball on the ground will have a potential energy greater than zero. Since both balls are stationary, their kinetic energy in both cases is zero." Let's try the first frame of reference.

But suppose the ball is in motion. Then to its potential energy we add the kinetic energy. However, the sum of both energies, called the total energy, will obviously remain negative if the ball does not jump out of the hole. On the contrary, it will become positive if the ball jumps up and rolls along the ground.

This lengthy explanation may be a bit tiring to the reader but it will help to clarify many things now and later. The point is that from the viewpoint of energy, an electron in an atom is like the ball in the hole. A free, independent, electron is like the ball on the ground. Physicists have agreed to reckon the energy of such electrons taking for zero the total energy of a free but stationary electron.

Of course, there isn't very much in common between an electron and a ball. Probably only that they are both constrained in their movements. The ball can't, of itself, leave the hole, and an electron cannot leave its atom. That is precisely why atoms exist.

The closer the ball is to the top of the hole, the farther it is from the bottom and the greater its total energy (which means, the lower the negative value of energy). The same with the electron. The farther it is from the nucleus, the higher its total energy; the closer it is to the nucleus, the lower its energy (but the greater its negative value, naturally).

To summarize, then, when an electron jumps to an orbit closer to the nucleus, it diminishes its energy, so that photons are emitted in just such transitions. And on the contrary, the farther the orbit is from the nucleus, the closer the electron is to 'escaping' from the atom, and the more energy the electron has. Now let us return to our story.

Excited Atoms

But again we have to deal with our ball. Why doesn't it fall? Which is a silly question, since there is nowhere to fall.

We have a similar situation with an atomic electron at low temperatures. There is nowhere to jump to. The electron is located in the orbit closest to the nucleus; from here the only place to fall is onto the nucleus, which is just as impossible as for our ball to fall through the earth.

The electron energy is at its lowest. The electron has nothing left to lose. Therefore, it cannot emit any light.

It is evident that the electron must first be in an orbit some distance from the nucleus so as to be able to fall closer to the nucleus. The question is: How does the electron get into an outer orbit? The same way that a ball can get to the top of a ladder, say: by us putting it there, which is to say, by giving it some energy.

The same thing goes for the electron. To put it into a distant orbit, we must give it some energy. More specifically, we have to impart to the electron a portion of energy that is at least as much as the energy difference between the two orbits.

There are different ways of delivering the energy. One common way occurs in the thermal

motion of atoms when one atom with sufficient speed collides with another, giving up the right amount of energy. At room temperature, such collisions are common, but the energy is too low. When the temperature reaches hundreds and thousands of degrees, collisions result in big exchanges of energy, electrons jump to new orbits, and light is emitted.

Energy has been imparted, the electron is in an outer orbit. Then what happens? The nucleus does not allow the electron to stay in the outer orbit for any length of time. It pulls it back into an inner orbit, and as the electron jumps inwards, a photon is ejected. Our eye perceives the photon and we say that the body glows, or emits light.

The body is now emitting light. Let us raise the temperature and see what happens. The thermal motion of the atoms becomes more energetic, collisions are more frequent and violent. The electron spends only a little time in its innermost orbit. The atoms more and more frequently go into a state which physicists call 'excited', then return to 'normal' only to leave it again almost immediately.

At this point, photons are being generated by thousands and millions every second. They build up avalanche-like as the temperature rises (recall the Stefan-Boltzmann law).

But it is not only the number of photons that is increasing. The lengths of the electron jumps also increase. The first timid jumps to neighbouring orbits and back again give way to record leaps to distant orbits, far away from the nucleus. Jumping back from such orbits the electrons generate very strong photons. And we know that the higher the energy of a photon, the great-

er its frequency and the smaller its wavelength. The emitted light becomes brighter and more 'violet' (recall Wien's displacement law).

Bohr's theory was thus able to account at one stroke for the basic laws of the theory of thermal radiation and spectroscopy. After this great success, the quantum nature of light and of atomic processes was obvious. In just a little while this was recognized by most scientists.

The First Setbacks

Yet it was still early to speak of a complete victory for Bohr's theory. The next ten years saw a tremendous development of the theory. There was a great expansion in the range of phenomena that it embraced. These included the most subtle processes of emission and absorption of light by atoms, and the detailed structure of atoms and molecules. In 1914, Kossel laid the foundations of quantum chemistry now included in every textbook on the subject. In 1916, Sommerfeld advanced a more exact theory of the origin of atomic spectra. To this day it helps decipher complicated spectra. The new theory was able to account for the newly discovered magnetic and electrical properties of atoms and molecules.

At the same time, the Bohr theory was encountering more and more difficulties. It was not capable of explaining many new facts, some of which were the ones that gave it birth.

The first was in the very spectra that Bohr's theory helped to explain. The trouble was that the explanation was not sufficient.

We have already mentioned that spectral lines are characterized not only by wavelength

but by brightness too. From Bohr's theory we could find the distance between the rungs of the energy ladder of electron orbits (that is, the wavelengths of the photons generated in electron jumps from rung to rung, from orbit to orbit). But the theory was helpless as far as accounting for the brightness of the spectral lines was concerned. It was not clear how one could calculate the number of photons in the spectrum.

It was obviously too early to speak of a victory for the Bohr theory over classical physics. Though he at first dispensed with the classics, he later had to revert to them. This was in the form of the so-called correspondence principle.

In a nutshell it was this. Classical physics was able to calculate the brightness of spectra, but could not account for their origin. Quantum mechanics was able to explain the essence of spectra, but could not calculate the brightness of the spectral lines. Bohr concluded that both theories had to be used, and that they should be harnessed together in areas where they more or less coincided.

But where did this occur? According to classical physics, an electron in orbit about the atomic nucleus would come closer and closer to it and finally fall onto it. In the process, it would emit a continuous spectrum with no single lines.

According to quantum mechanics, an electron in an atom radiates separate lines or, as we say, radiates a discrete spectrum. What have the two spectra in common?

The rungs of the energy ladder of electron orbits have different heights. The height is less, the farther the orbit is from the nucleus. The energy ladder in the atom is somewhat like a long ladder looked at endwise, in perspective,

so to speak: the rungs at the far end appear close together. In the case of the ladder, this is simply an optical illusion, while in the atom it is an actual fact.

But the height of the energy level corresponds to the energy of the photon or the wavelength of its spectral line. Thus, long wavelength lines of the spectrum, which correspond to electron jumps between orbits distant from the nucleus, must be close to one another, which makes it appear as an almost continuous spectrum.

Thus, the long wavelength section of the 'quantum' spectrum should not differ materially from the very same section of the 'classical' spectrum. In this region, the brightness of the first spectrum could be calculated on the basis of classical physics. And then we could extend the calculation to the entire 'quantum' spectrum. That is the correspondence principle.

It was a brilliant idea, only in practice the physicists were disappointed. Experiment yielded line brightnesses that differed from those of theory.

Generally speaking, it was hard to expect anything else. A theory that has to resort to outside help is not very strong. And one that has to go for help to its recent opponent is weak indeed.

To introduce classical physics into quantum mechanics is, as the English physicist Bragg once said, like preaching 'classical religion' on even days of the week and 'quantum religion' on odd days. Though science sometimes resorts to two gods and finds it useful, actually it is an indication of a weakness in the theory.

A closer look at the new theory will show that the correspondence principle was not the only lapse in Bohr's theory. Actually, from the very

start all its basic premises bore clear traces of classical physics.

Bohr rejected the classical views on electron motion, yet introduced the concept of electron orbits in the atom. He was firmly convinced that electrons revolved about the nucleus of the atom in the same way that the earth moves round the sun.

Bohr 'prohibited' the electron from radiating while in orbit, but he could not find any good justification for doing so. Bohr's theory gave a correct explanation of the origin of photons in atoms, but the process as such remained a mystery. It did not follow from any of its postulates.

This dual nature of Bohr's theory was quick to manifest itself. New facts cropped up that did not fit into the framework of the theory. Yet it had merits. Bohr's theory was a tremendous step forward in understanding the world of the atom. And it had its limitations. It explained much that was incomprehensible and beyond the means of classical physics. But almost as much remained unaccounted for.

The time for new steps had come. And they were soon made. The first was taken by the French physicist Louis de Broglie.

From Bohr's Theory to Quantum Mechanics

A Remarkable Article

In 1924, the September issue of the English "Philosophical Magazine" carried an article by an unknown physicist, Louis de Broglie. The author described the principal points of his dissertation, which was devoted to the possible existence of matter waves.

Waves of matter? Weren't they the commonly known sound, light and other such waves, which are quite material and which are perceived by our sense organs or are recorded by instruments?

No, it turns out that de Broglie had in mind quite different waves. The views expressed by de Broglie were so unorthodox and paradoxical that they could easily compete in originality with those put forward by Planck a quarter of a century before concerning quanta of energy. And not only as to their importance to physics, but also in the way they were received by very many physicists: open incredulity.

What are these matter waves, anyway?

Before going into them, let us take a look at 'ordinary' waves, which had been thoroughly studied by that time.

A Little about Ordinary Waves

Throw a stone into a pond and watch the waves move over the surface of the water. Incidentally, surface waves are practically the only type of wave that can be observed directly in motion.

It might appear that the water itself moves with the waves. But this is not so. Watch any little boy throw stones behind his toy ship hoping in this way to move it back to the shore. The waves move under the craft, which just bobs up and down in one place. This means that the water does not move away, but just up and down. In big waves produced by big stones, there is a little movement of the water, but never for any great distance.

This 'carrying' property of high surface waves is made use of in riding the surf, a sport common in Australia and elsewhere. The sportsman stands on a large board and moves up and down with the large regular waves moving in towards the shore. He gets onto a wave and moves towards the shore at a tremendous speed. But the slightest false move and he will find himself in the trough of the wave instead of on the crest.

In this risky, exciting sport, the wave carries the sportsman piloting him towards the shore. Remember the term, pilot wave. We shall return to it later on.

Last century, physicists learned that sound was also a wave motion. Sound waves were found to be propagated in the air, in water, and in solids. What is it that vibrates in sound waves? The particles of the medium through which the sound is propagated. Molecules of air, water, the atoms of solids.

Take away the air, water, matter generally, and sound waves disappear. There is no sound in a void. Future astronauts will probably observe grandiose eruptions of volcanoes on distant airless planets all in complete silence. Only the ground shaking under their feet will be felt. On the moon, spacecraft will start up in absolute silence. There will be no roar of rocket engines as we know it here on earth.

The physicists of last century likewise learned about the nature of electromagnetic waves produced by the movement of electric charges.

The light and radiowaves of distant stars and nebulae now arriving at the earth began their trip thousands and millions of years ago. Their pathways lay mostly through enormous and nearly empty interstellar spaces. On the moon, astronauts in complete silence will watch jets of dazzling fire eject from the bottom of their space rocket.

In a vacuum, one can see and not hear. That is the most fundamental difference between electromagnetic waves and mechanical waves, including sound waves. No intermediate medium is needed for the propagation of electromagnetic waves. On the contrary, a medium only reduces their speed.

Getting Acquainted with Matter Waves

Let us return to the matter waves.

De Broglie maintained that these waves are generated in the motion of any body, whether a planet, a stone, a particle of dust or an electron. Like electromagnetic waves, these waves are capable of propagation in an absolute void. Hence, they are not mechanical waves. But

they are produced in the motion of all bodies, including those not charged electrically. Hence, they are not electromagnetic waves.

At that time physicists did not know of any other kinds of waves. So these matter waves were indeed some sort of new hitherto unknown waves. Utter nonsense, said the old physicists with a shrug.

They were firmly convinced that all possible waves had already been discovered. This young Louis de Broglie speaks of waves of matter, but are not mechanical and electromagnetic waves, waves of matter? Without matter there are no waves, in fact there is nothing at all!

True, de Broglie didn't think up a very good name for his waves. But what could he do? New things get names before scientists have time to understand them properly.

That is exactly what happened to de Broglie. Those matter waves of his proved so intricate that physicists are still arguing about them. We shall have to take a closer look at the de Broglie waves because they are the foundation of present-day quantum mechanics.

Why Can't We See de Broglie Waves?

That was probably one of the first questions that physicists asked de Broglie. Well, how do we generally perceive waves? Not only by means of our sense organs, which are a rather poor instrument anyway. The human ear perceives sound waves with frequencies between 20 and 16,000 vibrations per second. These frequencies correspond to sound wavelengths in air of about 17 metres to 2 centimetres. The human eye

reacts to light waves of length from 0.4 to 0.8 micron. Those are nature's 'windows' as far as learning about waves goes (if, of course, we leave out the surface waves of the sea).

Physicists use special instruments to transform waves beyond the human range to lengths that lie within these two 'windows'. This greatly extends our possibilities of studying wave phenomena. Radio receiving sets pick up and allow us to study radiowaves of the metre and centimetre band that come to earth from the depths of the universe. Scintillation counters * enable us to detect gamma rays emitted by atomic nuclei. These are electromagnetic waves millionths of millionths of a millimetre long.

It is now clear that the range of wavelengths that have been studied is very great. Why, then, haven't we been able to detect the de Broglie waves?

The point is: How? Mechanical waves (sound waves, for instance) metres in length can be detected by the ear. But a radio, even when tuned to the given wavelength, cannot detect them. The radio responds only to radiowaves. And, looking at it from another angle, radiowaves are not perceived by the human ear or any other mechanical instrument, even if they are several metres in length.

Each type of receiver responds only to its specific type of wave. The ear responds to sound waves, the eye to electromagnetic waves. How does one detect the de Broglie waves, since they

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* Scintillation counters use special crystals for recording nuclear particles and gamma quanta. When a particle or quantum of radiation impinges on such a crystal, a flash, or scintillation, is emitted and recorded by sensitive instruments.

don't belong to either class? Actually, that is the answer to the question we started out with. Later on we will learn more about this.

We get another answer if we try to determine the wavelength of these matter waves. De Broglie obtained a relationship connecting the length of the new waves with the mass and velocity of the moving bodies. Here's what it looks like:

$$\lambda = \frac{h}{mv}$$

In this relation, lambda (λ) denotes the de Broglie wavelength, and m and v are, respectively, the mass and velocity of the body; h is our old friend, the Planck constant.

This is significant because it means that the de Broglie waves are of a quantum nature. We shall take up this question again later on. Meanwhile, let us find out what wavelengths correspond, according to de Broglie, to the motion of objects about us. Let us calculate briefly for a planet, a stone and an electron.

Just a glance will show that these wavelengths should be extremely small, since the numerator is Planck's constant, which is exceedingly small: 6.6×10^{-27} erg per second.

Let us take the planet earth. It has a mass of 6×10^{27} grams and a velocity of orbital motion about the sun roughly 3×10^{6} cm/s. Putting these figures in the de Broglie relation, we find the length of the earth wave to be

$$\lambda = \frac{6.6 \times 10^{-27}}{6 \times 10^{27} \times 3 \times 10^{6}} = 3.6 \times 10^{-61} \text{ cm}$$

That is fantastically small. No existing or foreseeable instruments could record anything that small. There just doesn't seem to be any

comparison to illustrate just how very small this figure is.

Let us see what the wavelength of a stone is like. Take a stone of 100 grams travelling at a speed of 100 cm a second. From de Broglie's formula we find

$$\lambda = \frac{6.6\times10^{-27}}{100\times100} = 6.6\times10^{-31}\text{ cm}$$

Not much better than the earth's de Broglie wavelength. Absolutely hopeless of ever being detected. It is a million, million, million times smaller than the atomic nucleus, which itself is far beyond the range of any microscope.

Now let us take the electron. It has a mass of about 10^{-27} gram. If an electron begins to move in an electric field with a potential difference of one volt, it will acquire a velocity of 6×10^{7} centimetres per second. Putting these figures into the de Broglie relation gives us

$$\lambda = \frac{6.6\times10^{-27}}{6\times10^{7}\times10^{-27}} = 10^{-7}\text{ cm}$$

This is something quite different. 10^{-7} cm corresponds approximately to the wavelengths of X-rays, which can be detected. Thus, in principle, we should be able to detect a de Broglie electron wave.

The Wave is Found

But how? The de Broglie wave exists in theory and there doesn't seem to be any way of detecting it instrumentally. But a wave is a wave and there must be some phenomenon in which it will manifest itself no matter what its nature.

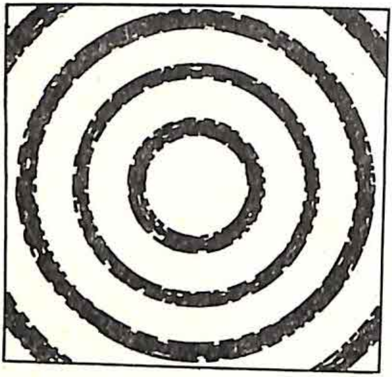
An attempt was made to catch the de Broglie wave in a diffraction experiment, the point being that diffraction is so completely a wave phenomenon. Diffraction consists in the fact that when a wave encounters some obstacle it passes round it. In doing so, the wave is slightly deflected from its straight path and moves into the 'shadow' behind the obstacle.

The diffraction pattern of waves from a round obstacle or a round aperture in a screen opaque to waves is typically a system of alternate dark and light rings. Such a pattern is seen, for example, when one looks at a street lamp through a dusty glass. On frosty nights, the moon is surrounded by several light and dark rings: the moon light has experienced diffraction on minute ice crystals dancing in the air.

Diffraction is a definite indication of the existence of waves. It was precisely the discovery of the diffraction of light at the start of the nineteenth century that served as a most convincing argument for the wave theory of light.

But the wavelengths of light waves are hundreds and even thousands of times greater than those of the de Broglie waves of electrons. All the devices constructed for producing diffraction of light—slits, screens, diffraction gratings—were much too crude. The dimensions of the obstacles used to observe diffraction of a wave must be comparable with or less than the wavelength. What is possible with light waves, is utterly out of the question when dealing with the de Broglie waves.

By 1924, it was known what objects to use in attempts to detect the diffraction of the de Broglie electron waves. Twelve years before, the German scientist Laue had noticed the diffrac-



X-ray pattern

Fig. 1.

tion of X-rays on crystals. Laue noticed a series of dark and light dots on a photographic plate exposed to X-rays that had passed through a crystal. Several years later, Debye and Scherer repeated Laue's experiment on small-crystal samples of powders, and obtained diffraction rings. In these cases, diffraction was possible because the distances between the atoms in the crystals (like slits in a 'screen' opaque to X-rays) were of the same order of magnitude as the wavelength of the X-rays: 10^{-8} centimetre.

But the lengths of the de Broglie waves lie precisely within this range! Which means that if these waves do really exist, then electrons, in passing through a crystal, should produce the same diffraction pattern on a photographic plate as the X-rays.

A few years after de Broglie advanced his new concept, the American scientists Davisson and

Electron diffraction pattern

Fig. 2.

Germer and the Soviet physicist P. Tartakovsky verified it in an experiment on the diffraction of electrons by a crystal.

However, in itself the analogy between the 'electron rays' and X-rays was not enough. The experiment required great ingenuity.

X-rays passed through the crystal almost unimpeded, while electrons were totally absorbed in a layer of crystal only a fraction of a millimetre thick. What was needed, therefore, was very thin crystal plates, or metal foils, or maybe to work with obstacles and not apertures. In this case, a beam of electrons was directed at a small angle to the face of the crystal so that the electrons sort of slid along it without going deep into the crystal and bouncing back from it. As a result, the electrons experienced diffraction only on atoms in the outermost layers of the crystal. The electrons that had experienced

diffraction were recorded on photographic plates.*

Tartakovsky sent a beam of electrons onto a thin foil consisting of a multitude of minute crystals. The exposure was several minutes long.

When developed, the photograph exhibited the outlines of real diffraction rings. These first plates—worth more than their weight in gold—were sent to the largest physical laboratories of the world. There they were carefully scrutinized. There was no more doubt. De Broglie's bold hypothesis concerning matter waves was brilliantly confirmed by experiment. Electrons exhibit the properties of particles *and* the properties of waves!

Two-Faced Particles

Even before these decisive experiments, scientists were trying to get at the real meaning of the de Broglie waves. How was one to understand this dual nature in the behaviour of particles, of electrons?

In those days, physicists knew what an electron was. A very small and very light particle of matter carrying a minute electric charge. For a long time no one asked what shape this particle had or what occurred inside it. There was no way of actually observing an electron, to say nothing of trying to figure out its internal structure.

But if an electron is a particle, then it obviously must have the properties of a particle.

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* Electrons can fog a photographic plate in the same way that visible light or X-rays do.

How could an electron have the properties of waves, something so utterly different?

The first attempt to interpret the matter waves was made by de Broglie himself. It clearly indicated that when physicists first entered the world of the ultrasmall they continued, from habit, to work with pictorial models. In the Bohr-Rutherford theory, the atom was like a planetary system in which the electron planets revolved about a sun nucleus, the only difference being that, unlike the planets, the electrons could frequently change their orbits.

But then came the light quantum, the photon. As Einstein had shown, it too possessed the properties both of waves and of particles. Obviously, such a dual object was beyond any pictorial representation.

Thus physics was confronted by the first unrepresentable entity. Now, with de Broglie's discovery, this unimaginableness had to be extended to particles of matter, from the tiny electron to enormous astronomical bodies. This was truly something to recoil from.

How could one even imagine that an electron flying at an obstacle would, as a result of diffraction, move round and get behind it. No, waves and particles were two mutually exclusive entities. A thing was either a wave or a particle!

And yet the de Broglie waves existed. It was not 'either or' but 'both'. Something had to be done to connect the unconnectable. And not for the single specific case of a diffracting electron. If an electron has wave properties, then so inevitably do all the objects of our world, from the smallest to the biggest.

De Broglie suggested beginning this unusual synthesis with the concept of a pilot wave.

Pilot Waves

Let's go back to riding the surf. The rider gets on the crest of a high wave that carries him to the shore. The wave acts as a pilot.

De Broglie's idea is that the matter waves pilot the moving particles of matter in a similar fashion. A particle, as it were, sits on a wave and moves wherever the matter wave carries it.

The length of this wave, de Broglie says, may be very great. At small velocities of motion of an electron, the length of the electron wave is many thousands of times greater than the electron. As the velocity increases, the particle, as it were, pulls the wave into itself, and the wave becomes shorter. But even at high velocities of motion the length of the electron wave is still greater than the 'dimensions' of the electron itself.

It doesn't exactly matter who leads whom, the electron the wave or the wave the electron. The important thing is that the wave is connected with the electron intimately and for all time. The electron wave disappears only when the electron stops. At this instant the denominator in the de Broglie relationship becomes zero and the wavelength, infinity. In other words, the crest and trough of the wave move so far apart that the electron wave ceases to be a wave.

The de Broglie picture is quite vivid: an electron riding its own wave. But where did the wave come from? It exists with the particle even when the latter is in motion in an absolute void. Which means that the wave is generated only by the particle itself. And how does that occur?

De Broglie's hypothesis has nothing to say on that score. Well, maybe the hypothesis can explain what interaction there is between a particle and its wave, how the wave moves together with the particle, how it shares the fate of the particle in the latter's interactions with other particles and fields, for example, when particles are incident on an obstacle or on a photographic plate. No, the hypothesis does not offer any convincing explanation.

In the search for a way out, de Broglie tried to throw the particle out altogether. Why not imagine the wave itself to be the particle? In other words, picture the particle as a compact formation of its waves, a wave packet, as it was called by physicists. A packet was to consist of a small number of rather short waves; when two or more packets collide they ought to behave like particles—exactly like a short-wave photon when it ejects an electron from a metal. But no matter how compact the packet, no matter how much it resembles a particle, it consists of waves. This surely means that there must be phenomena in which it will exhibit its primordial wave nature.

But nature rejected this proposal as well. It turned out that no matter how compact the wave packets are, they cannot form a particle. This is fundamentally impossible. The point is that these packets rapidly disintegrate in time, even in a total vacuum. In negligible intervals of time, a packet becomes so smeared out in space that the formerly compact particle is diluted to homeopathic proportions. Yet we know that particles are definitely stable, there is not a trace of any kind of spreading out in time.

This model too had to be given up. The mechanical combining of two such mutually exclusive entities as waves and particles into a single image was not a success. And it couldn't be. But that came later. De Broglie, however, did not want to give up his 'centaur' with the head of a particle and the body of a wave.

Two years passed. In the summer of 1927, physicists from all over the world arrived in Brussels at the Solvay Congress. At this congress, de Broglie's representation on the relationship between waves and particles was totally and resoundingly rejected. For many years to come, a completely different representation of this relationship led the way. It was presented at the congress by two young German physicists, Werner Heisenberg and Erwin Schrödinger.

Together or Separately?

Heisenberg and Schrödinger buried the de Broglie conceptions, but spoke so eloquently in doing so that this determined the whole subsequent development of quantum mechanics.

The principal idea of de Broglie concerning waves associated with the motion of bodies was quickly taken up by scientists in a number of countries. Hardly a year passed after de Broglie's first paper appeared when the German physicist Max Born proposed his own idea of the de Broglie waves.

Heisenberg, Born's pupil, who was just beginning his career in science, got interested in the problem. De Broglie's research was heatedly discussed by another group of physicists that included Schrödinger.

And then ... but we won't keep to the chronological order of events. The concluding episodes of a film shown at the beginning help to understand what is going on and heighten the dramatic effect.

Recall the experiment that proved the diffraction of electrons. In it an electron beam impinged on a crystal (or a very thin metal foil). The electrons of the beam experienced diffraction on the atoms of the crystal and impinged on a photographic plate fogging it and leaving diffraction rings.

We may now add that the electron beam produced by an incandescent metallic filament was specially formed. A diaphragm with a small circular aperture was inserted between the source and the crystal. As a result, after the electron beam had passed through the diaphragm it had definite cross-sectional dimensions.

What would have happened if we had stopped the experiment at the very start when there were only, say, several tens of electrons? When the photographic plate was developed we would see something like a target peppered with shot by an inexperienced rifleman. The dark dots correspond to the hits of separate electrons distributed over the plate quite at random.

Continuing the experiment, we would see a gradually emerging regularity in places where the electrons strike the target. After several thousand shots, the plate would reveal clear-cut dark and light rings, which were actually detected by scientists.

This is an interesting fact. Obviously, as long as the number of electrons participating in diffraction is small, no wave properties are exhibited. These properties appear only for large

numbers of electrons. In other words, the wave properties of particles seem to be manifested only by large assemblies.

To find the answer, we experiment again. The same experiment with diffraction of electrons but done differently. We can take a powerful source of electrons and expose a photographic plate for a short time. The diffraction pattern will then be formed quickly. Or we can take a weak source of electrons and lengthen the exposure time. But if in both cases the same number of electrons impinge on the plate, absolutely identical diffraction patterns will be produced.

This is very important. In the first case, when the electrons experience diffraction on the crystal all at once, one can speak of something in the nature of an assembly. But in the second case, when the electrons impinge on the crystal individually, the concept of an assembly is hardly applicable. What kind of a team of railway workers would you have if one welded one day, another moved a bolt the next day, and a third tightened it a month later?

The pattern is the same when the electrons undergo diffraction thousands at a time, and when they do it one at a time. The conclusion is obvious: each of the electrons displays its unusual properties independently of the others as if no other electrons existed at all.

A Visit to the Shooting Range

Let's take the target we spoiled. It was produced by a small number of electrons. At first glance, it would appear that the electrons impinged on the plate utterly at random.

But there is one thing that attracts our attention. We measure the aperture in the diaphragm from which the electrons emerged and project the outline onto the target. It would seem that all the electrons should fit inside this outline, no matter how randomly they had fallen on the photographic plate. Actually, however, many of the hits are far outside the boundary line.

And here is another interesting thing. If we examine the target carefully, it will be noticed that the electrons do not strike the plate in random fashion at all. Even when the number of hits on the target is small, there are blank places with not a single hit and there are closely bunched groups of hits. If a line is drawn through these places, little rings appear.

True, they are not well defined, but they improve as the number of electrons striking the plate increases.

Let's play a trick. Take an ordinary rifle target and punch holes where the electrons hit the photographic plate. Then show the target to a real marksman and see what his reaction is.

"What a funny way to shoot. Look at all those hits in number 10, and not a single one in 9 or 8. Was that done on purpose? All in 10, 7, 4 and 1?"

We don't say anything, and after a short while the chief marksman says, "Nonsense! No one could ever shoot up a target that way, no matter how he tried. And here's why. If the man is a beginner, his hits will lie at random, more or less evenly distributed over the whole target. The target of an experienced marksman looks quite different: a lot grouped around the bull's eye and just a few in the outer rings. Let's count the total number of hits in each ring of the target and construct a graph.

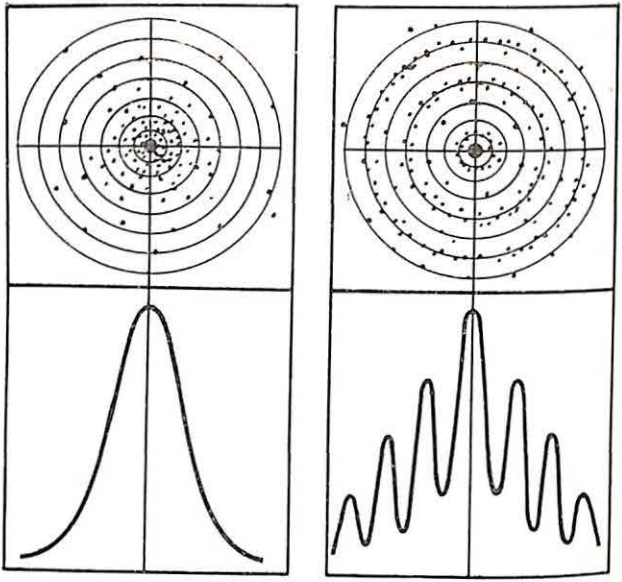

Fig. 3.

"On one axis we lay off the numbers of the rings (or the distance from the bull's eye, which is the same thing), on the other, the number of hits between two rings. We get a smooth curve downwards as we move away to the edges of the target.

"And now take your target. The graph in this case will oscillate up and down from the centre to the sides. The way it descends differs from our curve.

"In the case of our experienced marksmen the laws of chance hold true. And the curve we get is what is known as the curve of random errors,

or Gauss' curve. There is something random in your case too. But it obeys a different law, quite new to shooting ranges."

Now let's return to our target.

Waves of Probability

True enough, the wave-like curve is never encountered in shooting. Electrons are not bullets. A bullet has too big a mass for it to exhibit wave properties.

It was this distribution curve of electron tracks on a photographic plate after their reflection from the crystal that Born proposed calling the de Broglie wave.

Wait a minute! What connection is there between the 'paper' wave and the real wave? The real wave moves with the electron, while ours remains on paper.

However, they are related. The graph of electron hits on the photographic plate is not a figment of the imagination. It reflects the existence of a real wave associated with a moving electron. But the meaning of this wave is quite different from that which de Broglie gave it.

Classical Newtonian physics says very definitely that the electron emerging from the aperture of the diaphragm should move in a straight line until it hits the crystal. Then the electron is reflected from an atom of the crystal just about like a billiard ball bounces off the side of the table. Finally, the electron moves from the crystal to the photographic plate and leaves a track on it.

There is no human being here with shaking hand and tired eye. There is no wind or streams

of heated air coming up from the earth that could affect the aiming process. These are ideal conditions, and hence the accuracy should be ideal—all into the bull's eye. In other words, the electrons should reproduce on the photographic plate an exact outline of the aperture in the diaphragm. If the opening is a tiny hole, the photograph should reproduce a small dot and nothing more.

But the electrons refuse to follow the classical law. In place of a small point, we have a whole group of light and dark rings. This isn't due to inaccurate shooting. Even if we suppose this to be the case, the electrons would be distributed according to the Gauss law. In reality, however, they scatter according to a 'wave' law, which is quite different.

The distribution curve of electrons on the photographic plate is wave-like in shape. This same wave-form is exhibited by the intensity of the diffraction pattern due to light, and to X-rays, which are definitely waves.

Thus, the wave properties of electrons manifest themselves in a more subtle manner than de Broglie ever imagined. An electron wave is not an aircraft with an electron passenger. This wave determines the probability of an electron impinging upon some point on the photographic plate. A better name for it would therefore be 'probability wave', as Max Born suggested.

Probability Enters into Physics

In classical physics we never come across the term probability. The motion of every particle or body is considered to be rigorously and exactly

predetermined by the forces acting upon it. We can predict with absolute certainty the position and velocity of a body for any instant of time, a second later or a million years hence, if we know the forces acting upon it and the position of the body at the reference time from which we start reckoning.

But then in the middle of last century physics undertook the study of internal motion in gases. It was evident almost immediately that one could not apply Newton's equations directly to the motion of gas molecules.

Judge for yourself. Even small volumes of gas contain millions upon millions of millions of molecules. Now to give an accurate picture of their motion would require writing and solving the equations of motion of each of the molecules. The molecules are never at rest, they are constantly colliding with other molecules, bouncing off some, running into others; and these events occur millions of times every second.

It is preposterous even to imagine writing Newton's equations for all the molecules. Millions of years would be spent in just writing down the equations. More millions of millions of years in solving them. Meanwhile, of course, all these motions would have long since been replaced by others.

In the search for a reasonable way out, physicists saw that they should not be interested in the motion of each individual molecule of gas colliding with other molecules with unbelievable rapidity. Rather should their interest lie in the state of entire mass of gas: its temperature, density, pressure and other characteristics.

There is no need to determine the velocities of the separate molecules. All characteristics

of the state of the gas should refer to the whole system of molecules as an assembly. Now these characteristics are determined mainly by the mean velocity of the gas molecules. The higher the velocity, the higher the temperature. If, in the process, the gas does not change its volume, then there will be an increase in pressure with rise in temperature.

But to learn these relationships accurately, one had to find some way to determine the mean velocity of the molecules. Here was where the theory of probability came in.

It stated: "It is hopeless to think that all the molecules of a gas have the same velocity at every instant of time. On the contrary, they have different velocities and, what is more, these velocities are constantly undergoing change due to collisions. However, despite the random nature of these changes in velocity, there exists, at every instant of time, some mean, stable molecular velocity under the given conditions. What is random as concerns one molecule becomes a regularity when applied to a large number of molecules. Such is the probability law of large numbers. And the number of molecules in our volumes of gas is indeed large, in fact so large that the law can be applied without the slightest hesitation or doubt."

Physicists began to calculate the behaviour of large assemblies of molecules statistically, according to the laws of probability theory. But in one respect they did not want to agree with the theory of probability. They maintained that there was no randomness in molecular motion, that every collision, every individual motion of a molecule could be described by Newtonian laws and that if one desired to solve

millions of millions of equations, he could express these motions with absolute precision and without any kind of mean values. We don't do that, of course; but in principle it could be done! We describe the motion of a gas by means of probability laws, by the laws of statistics, but underlying them all are the exact laws of Newtonian mechanics.

Classical physics was just a little too sure of itself; there were simply no grounds for generalizing Newton's laws to the motion of individual molecules. The subsequent development of physics proved this. Molecules are not billiard balls. They move and collide and in doing so obey quite different laws.

Cautious Predictions

These were new laws, laws obeyed by electrons, atoms, and molecules. The first to 'rebel' were the electrons. They did not want to fit into the framework of behaviour of classical physics. Instead of hitting the photographic plate where they should, they ... "used their own free will and did what they wanted to!" shouted some scientists shocked by the disobedience of electrons.

Physicists weak in philosophy were easily led astray. Since the electron had a 'will of its own', there were no laws that it obeyed, a real anarchist. And if that's the case, why do we need science, which seeks laws, if there are no laws? God, they reasoned, had made the electron (and hence all things in the world) free to behave as it wished, free of all laws except one—the divine law of its existence. But science does not in-

vestigate this law, it grasps it by sheer faith. Quite a simple matter, you see—from the 'free will' of the electron to out and out idealism.

The materialists countered by saying that the new laws hold where the laws of classical physics fail.

This was predicted by Lenin. Twenty years before the time we are now describing he said that no matter what unusual electron properties might be discovered, they would mean only one thing—a deeper and more correct understanding of the surrounding world.

Electrons refused to follow the laws of classical physics, but they obeyed the laws of the new, quantum, mechanics.

What kind of laws were they? First of all, they were probability laws. What did the light rings on photographic plates (negatives) in the experiment with the diffraction of electrons signify? Simply that electrons did not strike these places on the plate. Obviously, the electrons did not act of their own free will, but were restricted in their behaviour.

Then we have the dark rings where most of the electron hits are made. But not all of the electrons impinge here. There are certain greyish places in between the darkest and the lightest sections. A 'mean' number of electrons impinge on these portions. We see this very clearly on the distribution curve of hits in our shooting game.

We now come to the most important thing.

An electron leaves its source, passes through the diaphragm, is reflected from the crystal and is moving towards the photographic plate. Where will it hit the plate?

Classical physics calculates the angles, distances and velocities with great accuracy and says

"Here." Which is usually not where it hits at all.

Quantum mechanics says: "I don't know exactly, but the greatest probability is that it will hit the dark rings, there is less probability that it will hit the grey sections, and it is hardly at all likely that it will impinge on the light rings."

Kind of overcautious. And it sounds strange for a science that wants to be called 'exact'. It doesn't even sound like science. How much nicer the 'absolutely exact' predictions of classical physics. Yet, if one begins to think about it, what arrogance in such predictions, what braggadocio and what ignorance too!

Indeed, what else can we say about a science which has just begun to investigate an infinitely complex world and which hardly knows anything about the events taking place in it, and at the same time makes such categorical statements.

But maybe we are, after all, a little too strict about classical physics. In the world of everyday things it does a very good job. And then again, it had no inkling, until just recently, of such things as quanta, the wave properties of particles, and many many other startling things.

True enough, every science aims at an exact and comprehensive knowledge of the subject under study. That is obviously the basic aim and motto. But there will never be a day when everything has been learned and there is nothing more for science to do.

That is the meaning of all these cautious predictions in science, all these 'possibles' and 'probables'. To speak of a probability means that our knowledge about a phenomenon is not absolutely complete and exact.

One can easily imagine the silly picture the weatherman would cut if he said: "Expect hot weather tomorrow, no rain, temperature at 9 AM, 23.8°C; at 12 : 00, 29.6°C; at 4 PM, 27.4°C. At 13 : 00 clouds will appear over such and such an area covering so many square metres during so many minutes. At 5 PM the clouds will move off in a north-easterly direction at a velocity of 12.3 km per hour."

There are dozens of factors that enter into the formation of the weather. In its present state, meteorology cannot take into account and describe with exactitude the many factors that make a perfect weather forecast. Far from it!

So much more difficult is the case of quantum mechanics, which deals with an immeasurably more involved world of the ultrasmall.

Waves of Particles and Particles of Waves

To get back to the de Broglie waves. They determine the motion of electrons. But they determine it in a probabilistic manner, not with perfect exactitude. In experiments dealing with the diffraction of electrons, these waves indicate areas of a photographic plate where the electrons will impinge with the greatest probability.

But wasn't Max Born mistaken when he took the 'waves of probability' for the de Broglie waves? Maybe the de Broglie waves are something quite different? If so, that's easy to check.

Let us recall the de Broglie relationship. From this relation we can see that as the veloc-

ity of an electron increases, its wavelength should decrease. Physicists already knew that the harder the X-rays, the shorter their wavelength and the more compressed their diffraction pattern. A study was made of the diffraction of electrons having different velocities. And here too, a tightening of the diffraction rings, as the electron velocities increase, was established quite definitely.

Now physicists could pass from the wavelength to the distance between the rings of a pattern, and vice versa. Calculations showed that if one computed the length of electron waves from the distance between rings, the result was values that coincided exactly with those found from the de Broglie relationship.

There was no doubt any longer. The 'probability waves' were the same matter waves that de Broglie had predicted. And they appear not only when electrons are diffracted by crystals, but are universal. They are associated with the motion of electrons and other particles of matter at all times.

But it is not always possible to detect them. The wavelengths of the de Broglie waves rapidly fall off with increasing mass and velocity of the particles, and lie beyond the sensitivity of our instruments. Then only the corpuscular properties of particles remain.

Recall our discussion of wave properties. Up to a certain point, waves (for instance, electromagnetic waves) do not exhibit any corpuscular properties and behave as waves should: they experience interference, diffraction, and so forth. But as soon as their wavelengths become small enough, they begin to act like particles and are able to knock electrons out of a metal.

The best example is gamma rays, the shortest of all known electromagnetic waves. With what ease they dislodge particles of matter, exhibiting true corpuscular properties.

De Broglie's discovery united into a coherent whole the world of physical phenomena, bridging the gap between two such opposites and, what would appear to be, mutually exclusive entities, as particles and waves. However, though the unity was discovered, there are no grounds for thinking that the opposites have disappeared.

They lie, as it were, deep within things and determine the bizarre physiognomy of the microworld, which is the world we shall be talking about very much from now on. We shall learn about marvellous things that are possible in the world of the ultrasmall and are very neatly described by 'waves of probability'.

On the Way to the Wave Law

These waves describe the motion of electrons and other particles of the microworld. Now how is one to understand the word 'describe'? A thing or phenomenon may be described both qualitatively and quantitatively. In ordinary life we usually do the former. When we hear "There'll be rain today", we pick up the umbrella and we don't ordinarily ask at what altitude the clouds will be.

But science, especially such an exact science as physics, is rarely satisfied with such a qualitative description. Figures are needed, and exact ones too.

So far we have described our diffraction pattern produced by electrons on a photographic plate mainly in a qualitative fashion, as alternate dark and light rings. We can also describe it quantitatively, by measuring the degree of darkness at different places on the plate and then plotting a curve, just like the one we made at the shooting range.

Now it would seem that we could produce a theory about this phenomenon and rest at ease. But it happens that there are other things that require an explanation. Science can't construct theories about each one separately.

In fact, therein lies the very strength of modern science: it builds theories that embrace hundreds of interlinked phenomena. The best and most powerful theories are those that are the broadest and most embracing.

In physics the construction of new and large theories often begins with the search for a single important formula. It is called the law of motion. A familiar case is Newton's second law, which connects the acceleration of a body with the magnitude and direction of the force acting on the body. But we don't actually see the force and accelerations, all we observe is the translation of bodies in space and time under the action of forces. It is this motion that Newton's law permits us to find. Acceleration is change of velocity of motion in time. And velocity is change of position of a body in time. So finally Newton's law relates a force to the actual translation of a body. And so when solving Newton's equation we find the type of motion of the body. It is expressed as a certain curve described by a body in a certain time. This curve is called the trajectory.

There is another very general and broad law in physics that describes not the motion of bodies but the propagation of waves. Mathematically, it is written in the form of the so-called wave equation, or d'Alembert's equation, after the noted French mathematician of the 18th century who discovered it.

Neither Newton's nor d'Alembert's equation is derived from any more general laws. They were not just thought up out of the blue, but were distilled, as it were, in a theoretical generalization of numerous experiments and observations made by the predecessors of Newton and d'Alembert.

A genius is not one who simply contrives things out of his head, rather is he one who perceives some hidden force, some law in an intricate maze of events, one who shakes that law free from its encumbrances, from accidentals and insignificant details, and polishes it clean as a compact formulation or (as in the exact sciences) a formula. The new law now is like a jewel of knowledge with elegant lines and brilliant facets.

What law was to serve as the cornerstone of the edifice of quantum mechanics? Naturally, for the new law of quantum mechanics to take the place of the laws of Newton and d'Alembert in classical physics it had to be at least as general and broad. What is more, this new law had to describe, all by itself, the two-faced world of the ultrasmall, supplanting the two earlier laws. This single law had to describe both the motion of particles and the propagation of waves!

No matter what you say, Newton had it easier. He had experimental facts galore, whereas here was a situation without a single experiment. The

year was 1925, and almost three years to go before the decisive experiment on diffraction of electrons. The de Broglie relationship was there, but all it described was the wavelength of particles, and nothing about particle motion.

However, theoretical physicists were so convinced that they were on the right path that they began the construction of the new theory without waiting for any experimental verification of de Broglie's hypothesis.

Maybe start by changing Newton's equation so as to include the wave properties of particles? No, history went differently. Physicists, following de Broglie, attempted to modify the wave equation so that it would reflect the corpuscular properties of waves. That proved to be simpler.

Schrödinger and Heisenberg were the first to achieve success in this respect. Their approaches were quite different. What is more, one probably didn't even know what the other was doing. It was only some time later, after their papers were published, that Schrödinger was able to prove that both solutions of the problem were physically identical despite the fact that outwardly they had nothing in common.

Heisenberg invented the so-called matrix form of quantum mechanics, which is very involved and far beyond the scope of this book. On the other hand, Schrödinger altered the wave equation so that the latter took into account the corpuscular 'taste' of the de Broglie waves. The new equation was called Schrödinger's equation and is the most popular equation of quantum mechanics.

Thus the wave law became the basic law of quantum mechanics.

Measuring Instruments Take over

Now let's get back to the de Broglie waves. According to the interpretation of Born and the final form of the Schrödinger equation, these waves manifest themselves for example, in the wave-like distribution of electron impacts on a photographic plate. But, as we have seen, one needs a lot of electrons to produce a clear pattern.

But of what significance is a de Broglie wave for a single electron? We know that too: it deflects the electron from the classical trajectory. Without this deflection there would not be any diffraction pattern at all.

That would seem to be clear. Yet there is something not quite satisfactory. After so much talk about the strange world of the ultrasmall, one rather wants the wave properties of the particles to be unusual in some way or another.

Well, let's see what the microworld has to say. Suppose we want to take a measurement. We are not interested in the specific type of measuring instrument. All it has to do is keep tab on the electrons, measure their velocities and positions in space at every instant of time.

The electron is a very small particle. It requires an ultrastrong microscope. Imagine we have created a microscope of the right power. Question number one: How are we going to carry out the measurement? To see an object, we have to illuminate it in some way. The point is: In what way? The illumination depends on the dimensions of the object. The first condition for a clear image is that the wavelength of light be less than the dimensions of the object. The ordinary light microscope operates with wavelengths of

from 0.4 to 0.8 micron, and therefore produces clear-cut images of objects at least about two to three microns in size.

But if we now take something say of half-micron size, the image will be blurred. When the dimensions of the objects are of the same order of magnitude as the wavelength of light, we have a strong diffraction of the light. Instead of a clear image we get a diffraction pattern, which consists of alternate dark and light bands that reproduce the outlines of the object.

Now take a still smaller object. The light goes past it as if the object didn't exist at all.

The electron is not a dust particle nor a bacterium; its size (later on we shall see that the term size is hardly appropriate) is roughly a thousand million times smaller than the length of light waves. So how do we illuminate it? Luckily, there are gamma rays with extremely small wavelengths.

So we take an electron for observation and light it up with a gamma ray, and we see nothing. Just nothing at all—there was an electron and now there isn't any. There aren't even any diffraction rings.

No matter how we try to produce an image of an electron, we'll never be able to do it.

The point is that an electron is not a dust particle and the gamma quantum is not a photon of light. The minute grain of dust has weight, and a photon carries some energy and, hence, some momentum.

Where does the photon get its momentum? We know that a photon can behave like a particle. This was already demonstrated by Einstein in his theory of the photoelectric effect. Judge for yourself: in empty space a photon

always has the same velocity, that of light, but its wavelength can be different. We apply to the photon the de Broglie relation:

$$\lambda = \frac{h}{mv}$$

where the velocity v is made equal to the velocity of light c. Then we can find the mass of the photon (this is naturally the mass of a moving photon; the rest mass of a photon is strictly equal to zero):

$$m = \frac{h}{\lambda c}$$

Now the momentum of a photon is the product of its mass by its velocity:

$$p = mc = \frac{h}{\lambda}$$

Now just a little more mathematics. From this formula it is readily seen that as the wavelength of the photon decreases, the momentum increases rapidly.

When a light photon hits a dust particle, it imparts to the latter its momentum and bounces off into the optical system of the microscope and into your eye. Our particle of dust doesn't even budge. If it was at rest, it remains that way; if it was moving, it hardly at all changes its direction of motion.

The electron is something quite different. Its mass is out of all comparison with that of a particle of dust; and its momentum is small even for a very fast electron. And so we fire a gamma photon at it with a momentum almost a thousand million times greater than a photon of light. When a gamma photon collides with an electron, forget about images or diffraction

rings. The electron is knocked right out of the picture, you might say.

We're not getting very far, and to make things worse we have to deal with velocity. Take an electron in flight; it is moving in some direction but we can't say with what velocity. We then illuminate it with a gamma photon and the electron changes its speed. Or, say the electron has zero velocity, it is at rest some place. But we can't locate it, because just as we illuminate it the electron is knocked off in some direction.

It was so nice with the old microscope. You have a dust particle or a bacterium, say, and you know all the time where it is and how fast it's moving. But try to locate an electron. We don't know its velocity, but if we try to determine it, we lose the particle altogether. Such are the tricks of the microworld.

The Uncertainty Relation

What we have just described is very close to actual fact. A little calculation with our dust particle and electron will show this to be true.

Take a little piece of dust one micron (10^{-4} cm) across consisting, say, of a substance with a density of 10 grams per cubic centimetre (just a little greater than the density of iron) and let it be moving in the field of a microscope with a small velocity of one micron per second. Then it will have a weight of 10^{-11} gram and a momentum of 10^{-15} gram per centimetre per second. We throw light onto it having a wavelength of, say, half a micron (in the visible light spectrum, this is green), its photons have momenta of only 10^{-22}, which is tens of millions

of times less than the momentum of our dust particle. It is clear as day that the photon impacts on the dust particle will not produce any effect whatsoever.

Now take the electron. Even if its velocity is close to that of light—10^{10} cm/s—it will have a momentum of only about 10^{-17} g·cm/s. The gamma photon used for illumination has a very short wavelength (say, 6×10^{-13} cm) and a momentum of 10^{-14}, which is thousands of times that of the electron. So when a photon hits an electron, it is like a railway train smashing into a baby-carriage.

By now it should be clear that the possibilities of measuring instruments in the world of the ultrasmall are limited, to say the least. They cannot measure particle motions with any degree of accuracy.

What are these inaccuracies, or, better still, uncertainties of measurement? The answer is given by the uncertainty relation derived by Heisenberg in 1927 from the general laws of quantum mechanics. Here is what it looks like:

$$\Delta x \times \Delta v_x \geqslant \frac{h}{m}$$

(Actually, the quantity $h/2\pi$ stands in place of h, but that is not significant, since there is only a sixfold difference between them.) Here, Δx is the uncertainty measurement of position (the coordinates) of a particle x; Δv_x is the uncertainty measurement of its velocity v_x in a direction x; m is the mass of the particle, and the sign $\geqslant$ signifies that the product of these uncertainties cannot be less than the quantity on the right side of the relationship.

Here is where the strangeness comes in. If we try to measure the position of a particle with

absolute accuracy, the uncertainty of its coordinate Δx must, of course, become zero. But then, by the rigorous laws of mathematics, the uncertainty of velocity becomes

$$\Delta v_x = \frac{h/m}{\Delta x} = \frac{h/m}{0} = \infty$$

—or infinity. Which means that the velocity of the particle at the instant when its position is being measured becomes absolutely indeterminate. Conversely, if at some instant of time we measure the velocity of the particle with absolute accuracy, we will have no way of saying where the particle was located at that instant.

Then what do we do? Maybe compromise by measuring both position and velocity of the electron with a certain inaccuracy, which on the whole will not be too great?

Let us see what the inaccuracies are for our dust particle and electron. For the former, the quantity on the right in Heisenberg's uncertainty relation comes out roughly to 10^{-15}. Now let us take the compromise values of uncertainty: $\Delta x = 10^{-8}$ cm, $\Delta v_x = 10^{-7}$ cm/s (multiplying them together we get, on the right, the quantity 10^{-15}).

The ratio of Δv_x to v_x is $10^{-7} : 10^{-4} = 10^{-3}$, which is one-thousandth part. This should satisfy us as an uncertainty in velocity measurements; few speedometers are capable of greater accuracy.

Now for the uncertainty in the position of the dust particle, Δx; its ratio to the dimensions of the particle is $10^{-8} : 10^{-4} = 10^{-4}$, which is one ten-thousandth. This inaccuracy corresponds to the dimensions of one atom in the dust particle.

That is why, when we measure velocities and positions of dust particles and more massive

objects, we never even imagine the existence of an uncertainty relationship.

But the electron offers quite a different picture. Its 'dimensions' (we again point out that it is not exactly correct to speak of the dimensions of an electron in the spirit of classical physics, which looks on the electron as a charged sphere) are approximately 10^{-13} cm across, mass—10^{-27} g, and the velocity of a medium-fast electron moving between a potential difference of one volt is of the order of 10^7 centimetres per second. The right-hand side of the uncertainty relation comes out to about 10.

There are different ways to construct this value out of the quantities Δx and Δv_x. For instance, suppose we want to measure the velocity of an electron with the same accuracy as we did for the dust particle, or 10^{-3}. Then our uncertainties will be: $\Delta v_x = 10^4$ cm/s ($10^4 : 10^7 = 10^{-3}$), and $\Delta x = 10^{-3}$ cm. The uncertainty in the position of the electron will be thousands of millions of times (!) the size of the electron.

Let us try to get the accuracy in velocity measurement up to 100 per cent, which is the actual velocity. As physicists say, this would give the order of the quantity being measured. Then $\Delta v_x = 10^7$ and $\Delta x = 10^{-6}$ centimetre, which is still millions of times the size of an electron.

No, there can be no compromise; the world of the ultrasmall doesn't want it.

What is to Blame, the Instrument or the Electron?

Classical physics never had to deal with dilemmas like this. It always considered that the position and velocity of any particle at any

instant of time could be measured with absolute accuracy (at least in principle). This lies at the heart of the predictions of particle movements on the basis of their positions and velocities at some initial point of time.

Now we find that even in principle there can be no talk of absolute accuracy of measurements. Where's the trouble? Maybe in the instrument?

True, no instrument is capable of measuring a quantity with absolute accuracy. We might say that the history of the development of measuring techniques has been a history of constantly increasing instrumental accuracy. Precision measurements in many fields of science and technology have today reached a fantastically high degree, and they are getting better all the time.

But it would seem that the uncertainty relation puts a limit, an upper limit, on the accuracy of instruments.

In this situation, Heisenberg (and other physicists after him) said that the trouble was in the instrument. The instrument for the microworld differs from the telescope used to study the universe. Both instruments are needed, of course. Our sense organs, which we use to study the world about us, have their limitations. In fact, that is what an instrument is for: to translate the phenomena within its range into 'human' terms of feeling.

But whereas the telescope does not in any way affect the motions of the astronomical bodies it observes, the microworld is quite a different proposition. There, our instrument (let us say our ideal supermicroscope) interferes directly with the phenomenon under observation and alters its natural course. What is more, it changes

it to such an extent that we have no way of separating out the phenomenon in pure form. That is what the uncertainty relation does, it puts an upper limit on the 'purity' of an observation.

Other physicists said: "The troubles lie with the electron." And their argument was rather convincing. The world of the ultrasmall lives according to its own laws and, generally speaking, does not require measurements for its existence. When we say that an electron has wave properties, what does that mean?

Well, take the oscillation frequency of a pendulum: to say that the frequency at a given instant is such and such is nonsense. To determine the frequency, one has to observe the oscillations of the pendulum for some time. Similarly, one cannot say that the wavelength at a given point is such and such. The very meaning of wavelength is that it is a characteristic of a long (strictly speaking, an infinitely long) series of waves. No matter what the nature of these waves, their length cannot depend on the position of any one point in the wave.

Let us take the de Broglie relation and write it so that we have the velocity of the particle on the left:

$$v = \frac{h}{m\lambda}$$

We immediately conclude that since the wavelength λ is independent of the position of any point in the wave (for example, the point at which we believe the particle to be), its velocity cannot be dependent on the position of the particle.

The failure of the instrument is due precisely to the wave properties of the electron.

So who is right? Those who accuse the instrument of not being able to adjust itself to the microworld, or those who blame the microworld as being inaccessible to measurements?

It appears that both are to blame, but only half and half. The truth of the matter is that the Heisenberg relation exhibits the 'guilt' of both instrument and electron. But that is not all.

An Attempt with Rather Faulty Tools

What do we require of an instrument? First of all, that it should provide us with the information that we wish to know. An instrument, of course, has no independence whatsoever, it only obeys the human will.

The instrument that we wish to use to investigate the microworld has two aspects, or two ends: an input and an output. At the input it deals with phenomena that obey quantum laws, at the output it releases information recorded in classical 'language', for our sense organs don't understand any other language.

We asked our instrument to inform us at every instant of time about the position and velocity of our electron. The instrument says very honestly that he cannot do that. He says he can provide information about velocities without indicating positions when the velocity measurements are made, or about positions, but with no information provided about velocities at that instant.

If one gives it a little thought, it is obvious that physicists themselves are to blame more than anyone else. They demanded that the instrument report on electron velocity versus

location, but it turns out that these two quantities are not related in any way.

Therein lies one of the wonders of the microworld, one of the manifestations of the wave nature of particles. In short, the old classical concepts and quantities that physicists had manipulated with ease for hundreds of years were no longer any good when dealing with the world of the ultrasmall.

Well, not exactly 'no good'. The concepts remain in the microworld as well, but they are in a way circumscribed, limited. The limits to which they can be used are established by the uncertainty relation.

The electron could be considered a point particle and one could say definitely that it had an exact position in space if it were not intimately associated with a wave. The wave, as it were, smears out the position of the electron: it can be located at any place of its own wave.

As a result, for an electron at rest its waves extend to infinity, and any attempt to find it at any definite place must fail. On the other hand, the faster an electron moves, the more accurately it is 'localized' in its wave. But even at the very highest velocities of motion its 'smearedness' is still many times greater than its own 'size'.

Not only the classical concepts of position and velocity of an electron are found to be insufficient in the world of the ultrasmall. Even time, the energy of particles, and many other notions undergo change in this new world.

Why, you may ask, didn't physicists disregard the old, classical concepts and quantities that don't function normally in the microworld

and replace them with new ones more in accord with the unusual properties of this world?

It is hard, at once, to see just how complicated this problem is, for it concerns the very nature of the process of human cognition. We shall come back once again to this towards the end of the book. For the present, it must be said that any change of conceptions and notions in physics or in any other branch of science is an unusually long, involved and trying process. Many thousands of years passed before man's first naïve ideas about the universe, the essence of life, of nonliving nature, and the structure of atoms underwent a change. One can easily imagine how naïve our own conceptions will appear to the world hundreds of years hence.

In our age, human knowledge is advancing at a fantastic rate. Still, the process of revealing new worlds, new phenomena lags behind, becoming more and more difficult and contradictory. As Einstein so aptly put it: "A Drama of Ideas".

That is exactly what happened when the classical concepts were taken into the world of the ultrasmall.

Another Marvel

Kids will jump over fences to get into a cherry orchard. And so the owner builds a higher fence. Now what does Johnny do? He takes a running jump, or he gets a ladder, or climbs a tree and jumps over, or ... well, there are a lot of ways, really. Boys today don't believe in fairy tales any more, but if they dealt with the world of the ultrasmall they certainly would have to imagine particles getting through 'solid' walls!

Let's take a closer look at this business of climbing or jumping over fences. From school we know that the lower a body is, the less its potential energy. Standing on the ground, you have less potential energy than when sitting on a fence. And we know how much less: this quantity is given by the product of the weight of our body by the difference in height of the centre of gravity of the body in the two positions; the difference is roughly equal to the height of the fence minus one metre.

If you find the energy some place, you can get over the fence. This can be done by using your own muscles or those of your companions to boost you up. In either case, the work done goes to increase your potential energy and you can get over the fence.

The rest is easy. Jumping down doesn't require any effort. On the contrary, it takes some effort to soften the descent against the force of gravity. Now the potential energy on the other side of the fence has diminished to what it was before the jump upwards.

If we plot our potential energy as we go over the fence, we get a rise. In physics this is called a potential barrier.

In the atomic world there are fences of this nature. For example, a metal contains a multitude of almost free electrons that are relatively feebly bound to their atoms. But, despite their freedom, no one ever heard of electrons leaving the metal of their own free will. The point is that the electrons are not completely free. Though the bond is weak, the electrons are still attracted to the ions that thus appear (this will be discussed in more detail in the next chapter). The overall action of all the ions on all the

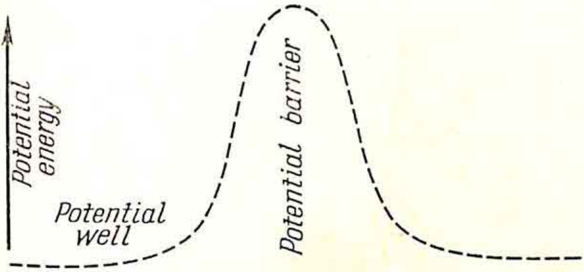

Fig. 4.

electrons in a piece of metal may be pictured in the form of a yard cut off from the outside world by a high wall with electrons running about inside the yard.

Electrons in a piece of metal resemble the balls in the hole that we discussed in connection with Bohr's theory. Inside the metal, the electrons move at random, but they can no more get out than our balls could leave the hole they were in. For this reason, the conditions under which the electrons find themselves in a metal are termed a potential well.

Still, these electrons are not really 'chained' to the metal for all time. Under certain conditions they can jump over the fence and get outside, as it were. For instance, this occurs when the metal is illuminated with light of sufficiently short wavelength. An energetic photon can knock an electron right over the potential barrier and make the electron really free. This is the conventional, classical way of getting over the potential barrier and does not really differ from kids climbing over a fence.

You've probably already noticed that in the case of electrons in a metal the barrier is not

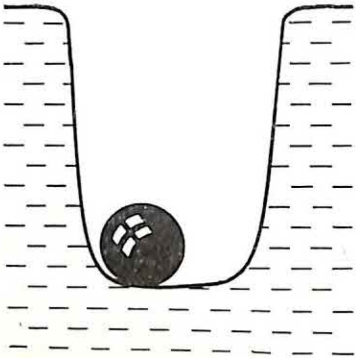

Fig. 5.

exactly like a fence: it has a front part but no rear part. It is more like a step than a fence. For the ball in the hole, we can make a fence by digging up the ground around its edges. In the case of electrons in a metal, this can be done by applying to the piece of metal a strong electric field.

Now both barriers—that of the ball in the hole and the electron in a metal—are very much alike. However, their similarity ends here.

If we solve the Newton equation for the ball in the hole, it will show that the ball will remain there for ever if sufficient energy to overcome the barrier is not imparted to it. We know that without any equations. Balls don't just jump out of holes, neither do boys get over fences without jumping.

Classical mechanics firmly states that the ball will never get out of the hole, that the probability of this 'wonder' is zero, which means complete impossibility.

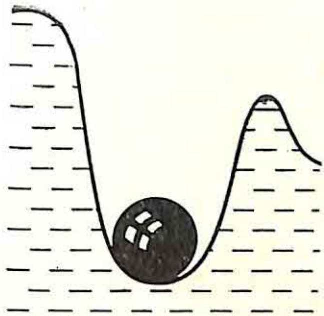

Fig. 6.

Now if we solve the Schrödinger equation for an electron in a metal placed in an electric field, the result will be quite unexpected. Here, the probability of an electron getting out of the metal is not equal to zero and, strictly speaking, never actually becomes zero. It is very small, maybe negligibly small, but it never vanishes! The electrons would seem to be able to seep through the potential barrier, as it were, and get to the other side, in complete derision of the predictions of classical physics. Mysterious forces would seem to have cut a tunnel through the barrier to let the electron through. Hence the name physicists gave to this amazing phenomenon—the tunnel effect.

The Uncertainty Relation Once Again

While we wait for quantum mechanics to explain this new 'wonder', our measuring instrument has been at work, but the results are

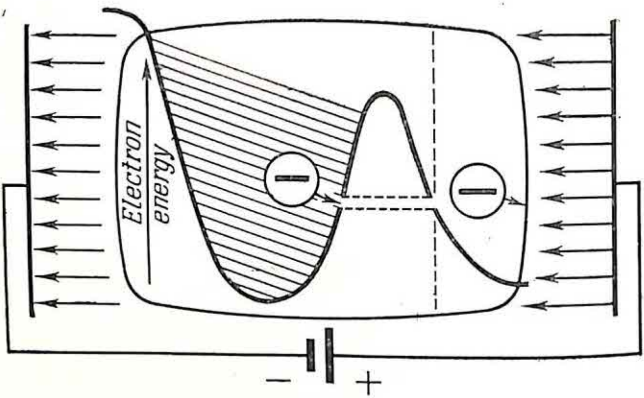

Fig. 7.

very discouraging. We asked our instrument to see how the electron seeps through the potential barrier, since this violates the most fundamental laws of classical physics. We wanted to be sure that this was nothing other than theoretical nonsense.

We have already mentioned that the total energy of the ball in the hole is equal to the sum of its kinetic and potential energies and is negative. This is because the potential energy of the ball (which we reckon from the top of the hole, that is, from the highest point of the potential barrier) is negative and exceeds (in magnitude) the kinetic energy of the ball. It is clear also that within the limits of the barrier the total energy of the ball should remain negative, since in the process of seeping through it does not change in magnitude. But, on the other hand, the potential energy decreases until at the uppermost point of the barrier the total energy comes zero.

The only conclusion is that within the limits of the barrier the kinetic energy of the ball became negative. But what kind of a quantity is that? Let us write it down:

$$E_{kin}=\frac{mv^2}{2}$$

The square of the velocity v is always positive no matter what its sign, the two in the denominator is also positive. Which means that the mass of the particle m is negative. But negative mass cannot be imagined either in classical physics or the most revolutionary quantum mechanics. Just picture to yourself a train going from Moscow to Leningrad, while the cars are moving away from the locomotive, from Leningrad to Moscow!

Definite nonsense! And to make sure that it is, we set up an instrument to watch the electron. The instrument has detected the electron and begun its observations. Here's what happened. The electron approached the boundary of the potential barrier. To catch the electron when it is seeping through the barrier, it is not even necessary to fix its location; make sure that it is located somewhere within the limits of the barrier.

But that is not all. The instrument must find out the velocity of the electron at that instant in order to determine whether its kinetic energy indeed becomes negative. Here the instrument is helpless. Only the Heisenberg uncertainty relation can save the situation.

Now in order to fix the location of an electron within the barrier, the electron must be illuminated by photons of short wavelength, because it is required to determine the position of the

electron with an accuracy not less than the width of the barrier itself and this width is small in the world of atoms. But the impact of a photon on an electron will introduce an appreciable uncertainty into its velocity, which will be such that the uncertainty it causes in the kinetic energy of the electron will be just enough to get over the highest point of the barrier.

In other words, there is no way of detecting a particle in a nonclassical passage under the barrier. In the very process of 'detecting' it, an energy is imparted to the particle sufficient for the latter to jump over the barrier in a perfectly lawful and classical manner. Almost like a policeman helping a criminal cover up evidence.

The foregoing is typical of many things that occur in the world of the ultrasmall. From the viewpoint of classical physics, quantum mechanics can assert the most fantastic things. And it is fundamentally impossible to prove the falsity of these assertions by the use of classical instruments. Don't look for the particle under the barrier, you won't find it. The very concept of a particle inside a potential barrier is just as nonsensical in quantum mechanics as in classical physics.

Yet the particle gets through the barrier! The clue to this mystery lies, in the final analysis, in the wave properties of the electron and of the other particles of the microworld.

Matter Waves Again

As we have already seen, these wave properties result in the particle velocities ceasing to depend on the positions of the particles. There

are no trajectories in the world of the ultrasmall. But the position of a particle affects its potential energy, and the velocity, its kinetic energy.

And so, strictly speaking, it is impossible at one and the same time to measure accurately both the kinetic and potential energies of a particle. They are independent of each other at any given instant. Within the limits of applicability of these classical concepts, energies in the atomic world are given by the uncertainty relation.

All this means that a particle in a potential well has a certain probability of getting outside the well, all by itself. Which means also that there is a probability that the particle will remain in the well. If, say, we have a thousand electrons and ten of them get through the barrier, then the probability of the tunnel effect is 1 per cent, and the probability of no tunnel effect is 99 per cent.

These probabilities are called, respectively, the penetrability and the reflecting power of the potential barrier.

Penetrability, or transparency, and reflecting power are familiar terms. They describe substances with respect to the passage of light waves. At the interface of two different substances, light always partially passes into the second medium, and is partly reflected. And isn't the potential barrier a boundary between two media? Simply not for electromagnetic (including light) waves, but for the de Broglie waves.

This is a very profound analogy. The laws of the tunnel effect coincide remarkably with the laws of reflection and transmission of light waves between the boundaries of different substances.

The fact that we chose a fence, i.e., something of a definite finite width, for our barrier is not accidental. If this barrier has only a front wall, like the step of a staircase, the tunnel effect disappears completely. Particles cannot construct tunnels in infinitely long (though very low) barriers. Here the prohibition of classical physics is complete.

Indeed, our measuring instrument would be able to celebrate something like a victory: it would be possible to establish the location of a particle under the barrier (if it got there) with complete assurance, no matter how great the uncertainty in the measurement of its position. Which means that the uncertainty relation would yield the exact speed and, hence, kinetic energy of the particle. This energy would then definitely be negative.

But nature will not contradict itself. Negative kinetic energy is an impossibility. And so the tunnel effect disappears.

Yet, maybe some readers are not convinced by the foregoing explanation. Can it be that everything we've said is just abstract theoretical thinking? Well, judge for yourself. Electrons leave a heated metallic filament in large numbers—the thermal energy is sufficient for them to get over the barrier at the boundary of the metal, though this will never happen in the case of a cold metal.

But put this piece of metal into a strong electric field and there will again be a flood of electrons out of it. This is called cold emission and marvellously corroborates the fact that the tunnel effect is no fictional fancy of theoretical physicists.

The Wave Function

Equations are not formed for the fun of it, but to solve. And Schrödinger's equation is no exception. Equations are sometimes simple, sometimes involved. Schrödinger's equation is definitely complicated. It is known as a second-order partial differential equation. To explain what all this means, is much beyond the scope of this book. Suffice it to say that equations of this kind are used to describe quantities that vary in space and in time.

The unknown quantity in these equations may be disguised in all sorts of ways: it may be the form of the surface of a liquid in a vessel, the coordinates of a satellite in outer space, the strength of a radio signal moving from transmitter to receiver, the cutting speed of a machine tool, and many other things. The solution of such an equation yields directly the dependence of the sought-for quantity on other quantities of interest to scientists. Mathematicians use the term function to describe all of these relationships.

The unknown quantity in the Schrödinger equation is called the wave function. Its exact meaning is still not clear to scientists despite the fact that thousands of elegant calculations have been made with it. We have already said that scientists are still arguing about it.

However, there is one thing that they all seem to be agreed upon, that is that the square of the wave function has the meaning of probability. Its dependence on the coordinates and time yield the probability of finding a particle at some place at a given time. More precisely: the probability that a particle may be detected

in a given place at some time due to the action that it performs there. For example, due to its interaction with our measuring instrument. This probability is the 'wave of probability' that we described in the experiment of diffraction of electrons.

To solve the Schrödinger equation in the general case is an exceedingly difficult problem, even when we use the most refined methods of modern mathematics. But there is a broad range of phenomena that make this solution easy. The so-called stationary problems in which the desired wave function only oscillates about a definite 'mean' form while the form itself does not vary in time.

It is quite easy to see that such problems do not refer to processes (nonperiodic, of course). In processes, something is directed and varies in time. Stationary problems refer to the structure of systems in which processes can occur. It is very important to know the structure, since one cannot say anything about a process unless he knows under what conditions it occurs.

In the world of the ultrasmall, the elements of these conditions consist of nuclei, atoms, molecules, crystals, and many other things. We know that they all have a remarkably stable structure. The stationary Schrödinger equation was first applied precisely to such elements. Most interesting results were obtained. We shall discuss them in the next chapter.

Waves and Quanta are United

Stationary problems in quantum mechanics have yet another remarkable property. To understand it, we recall that the uncertainty

relation embraces not only, say, the position and velocity of a particle, but also its total energy and the time.

In the latter case, the Heisenberg relation states that the longer a measurement is made, the more accurate will be the resulting energy of the particle. The form of this relation is very similar to that given earlier:

$$\Delta E \times \Delta t \geqslant h$$

(again, in place of h it is more correct to write $h/2\pi$). Here, ΔE is the uncertainty in the energy E of the particle, and Δt is the uncertainty as to the instant of time t at which the particle had the exact energy E. The sign $\geqslant$ means that the product of these uncertainties cannot be less than h, Planck's constant.

Now stationary means that the energy of a particle does not vary with time. In principle therefore we could measure for ever. Here, the indeterminacy of the time of measurement does not play any part.

So we calmly put $\Delta t = \infty$. But then, by the rules of mathematics,

$$\Delta E = \frac{h}{\Delta t} = \frac{h}{\infty} = 0$$

which means that the uncertainty in measuring energy is equal to zero. In other words, under stationary conditions, the energy of a particle is determined with absolute exactitude. This is the remarkable circumstance that we just mentioned.

In the Schrödinger equation, the magnitude of this energy is a very active participant. As long as E is positive (and this, as we recall, corresponds to the free motion of a particle), Schrödinger's equation has a nonvanishing solution for any values of E.

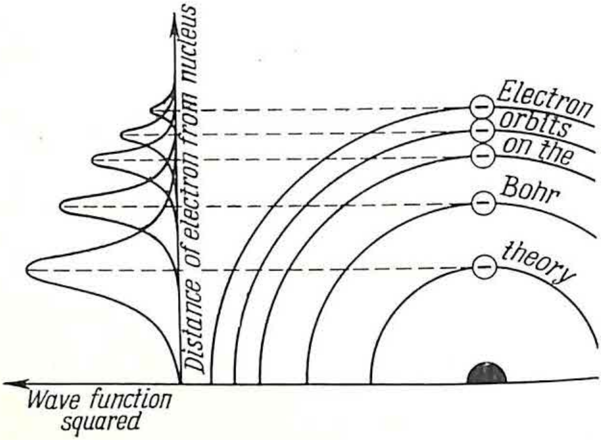

Fig. 8.

And this means that the square of the solution (the probability) is likewise nonzero for all values of E. Translated into ordinary language, this means that a free particle has the right to have any energy and any velocity of motion (which, naturally, can never exceed that of light) and be located at any place in space.

Now when E becomes negative (this, as we recall again, corresponds to the bound state of a particle; for instance, the ball in the hole, an electron in an atom), the solution of the equation changes radically. It appears that it does not vanish only for certain specific values of the energy E.

These values of E are called allowed energy levels of the particle. Take a look at the figure. The probability of the existence of a particle is nearly everywhere close to zero, with the exception of states in which it has allowed energy.

Here, the probability is noticeably different from zero. Physicists have termed this situation the discreteness of energy levels.

Now take a closer look. Doesn't this picture in some way resemble the permitted energy levels of the Bohr model of the atom? It certainly does. What is more, it is the selfsame thing. The electron orbits of Bohr are the very same energy states in which the probability of an electron being there is substantially different from zero!

Bohr simply conjectured these orbits, but he was not able to prove why they should exist. It is quantum mechanics that slipped the foundation under this hypothesis.

Quantum mechanics also substantiates Bohr's second postulate concerning the quantum nature of electron jumps in atoms. As can be seen from the Schrödinger equation, an electron in an atom can exist only in states of allowed energy. Which means that when transitions are made from one state to another, the energy does not change at random but in very specific quantities. It is simply equal to the energy difference between the states of a jump or transition.

This energy difference is precisely the Planck quantum that initiated the new physics! Quantum mechanics united two brilliant hypotheses—that of the Planck hypothesis on energy quanta and that of de Broglie on matter waves—and demonstrated their intimate interrelationship.

Without the de Broglie waves there would be no Planck quanta!

Thus it was that these two rivulets merged into a mighty stream of new knowledge. Let us follow this broadening river and see what new landscapes open up.

Atoms, Molecules, Crystals

Clouds in Place of Orbits

Hardly any other branch of physics has known such rapid developments as quantum mechanics. In something like five years following the birth of de Broglie's ideas, the methods and mathematical apparatus of quantum mechanics were worked out in every essential detail, results of great scientific value were obtained, and far-reaching attempts were made to assimilate these results.

By 1928, quantum mechanics was already a towering edifice, a fully established, mature science with a diversified foundation and a nicely proportioned superstructure substantiated in no less degree than classical mechanics. It took two hundred years for classical mechanics to reach this stage of perfection, and only five years for quantum mechanics. Such was the pace of the twentieth century!

And like a mountain torrent that breaks through a dam and then peaceably spreads out over the countryside, so quantum mechanics, after five years of tempestuous development, settled down. Development became more even as it

drew into its sphere of action new groups of phenomena, mastering them and interpreting them afresh.

The first gain of quantum mechanics was the atom. The new physics, under Planck and Bohr, began with the atom. The atom was the first object of interest to quantum mechanics.

Its first job was to reconsider the structure of the atom in its new light. Bohr introduced the concept of electron orbits. This, as we now know, was an inconsistent step and savoured of the classical physics. Quantum mechanics does not deal in orbits, it rejects them outright. An orbit is actually a trajectory of motion of an electron in an atom, while quantum mechanics quite rightly maintains that the conception of particle trajectories in the microworld is meaningless.

What supplants the orbits then? Distributions of the probability of an electron being located at some place in the atom. We already know that the total energy of an electron in an atom is determined by its distance from the nucleus. The set of allowed energies corresponds to the set of permitted distances from the nucleus.

Yet somehow we feel reluctant to give up the orbits completely, they make it so easy to visualize the atom. Quantum mechanics says: "All right, if you like orbits, keep them. Draw a line through those points where the probability of an electron with given allowed energy is greatest. Consider this line to be your orbit. But never forget that your electron is not a point; its own wave smears it out, so that your orbit is actually a fiction."

O.K., we thank the quantum people and draw our orbits. We are happy about our elegant

system of curves. Then the quantum man adds: "You know what makes these orbits interesting? They are such that an integral number of the electron de Broglie waves fit exactly onto each one of them. The first orbit, closest to the nucleus, accommodates one wave, the second, two waves, the third, three waves, and so forth."

This is indeed very interesting and serves as new proof of the universality of the de Broglie waves.

But then the quantum man says: "Your pictorial orbits are pretty good. But don't get overenthusiastic, because they just do not exist. Instead of an electron in orbit, try to picture to yourself a 'cloud of probability'. Which is exactly what the electron in the atom is. The cloud is denser where there is more probability of the electron existing, and more rarefied or transparent where the probability is lower. Take a look at the photographs of these clouds."

Photographs? So they did finally succeed in catching these elusive electrons after all? Well, not exactly: there is no way of getting around the uncertainty relation. These are not photographs of atoms, but of special smoke models which are outwardly similar to the density distribution of 'clouds of probability' of atomic electrons.

In these pictures we see that the electron clouds have different shapes. Some of them are spherical, others are oblong, cigar-like. This diversity is due to the fact that the electron energies in atoms depend not only on the distance from the nucleus.

Incidentally, this is true of the simplest of atoms, the hydrogen atom, where there is only one electron in the field of its nucleus. Their

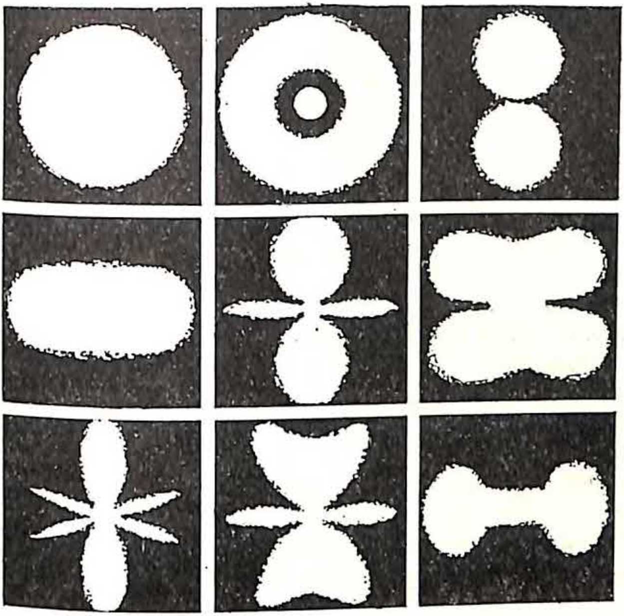

Fig. 9.

interaction is that of two charged particles of opposite sign but of the same magnitude.

This interaction is described by the Coulomb law. The energy of this interaction is dependent solely on the distance between the electron and the nucleus. It is clear, then, why the electron cloud of the hydrogen atom is spherical in shape: all points of the surface of a sphere are at the same distance from the centre, which in our case is the nucleus. Therefore, all points of the electron cloud correspond to the same electron energy.

But when there are more electrons in the atom, the picture of electrical interactions among them and also with the nucleus ceases to be so primitive as in the hydrogen atom. The electrons now are not only attracted to the nucleus but are repulsed by each other.

Naturally, in the multielectron family of a complex atom, all the electrons are particularly attracted to the centre of the family—the nucleus—although they quarrel among themselves. Nature very wisely plays on these strained relations and brings order into atomic families.

Just what this order is like we can see in the photographs. The electron clouds have very intricate shapes, which penetrate each other in involved ways. If we could put this picture into three dimensions and colour the different parts differently, we would stand in wonder before the marvellous colourations. Yes, quite unlike the prim picture of electron orbits.

Monotony in Diversity

It may be pleasing to the eye, but it is no mean job to figure out where one cloud begins and where the other ends in this maze of electrons.

Let us look into the workshop of the 'atomic architect'—nature—and see how he constructs such miniature marvels as these colourful tough structures called atoms.

The material of construction in the hands of nature consists of electrons and nuclei. The cement that keeps them together is also known: the attractive force of the electrons to the oppositely charged nucleus.

The first thing to catch our attention in the workshop of our architect is a huge sheet—the Periodic Table of elements of Mendeleyev. To date, 104 squares have been filled, 104 chemical elements are known.

These are the blueprints that nature uses to turn out the myriad atomic structures of the universe. Over a hundred blueprints!

They look different only at first glance. Nature is more economical than the most rationalizing architect.

First of all, let us figure out the basic principle which the atomic architect applies in placing his bricks into the edifice of the atom. This principle was discovered by the Austrian scientist Wolfgang Pauli during the formative years of quantum mechanics and was named in his honour.

It is applicable both to atoms and to many other assemblies of particles of the microworld. The Pauli principle states: in any assembly of microparticles, each state of allowed energy can be occupied by no more than one particle.

True, it was found later on that this principle is not absolutely universal, and that for certain types of microparticles it does not hold. We shall not talk about the exceptions, but will only say that as applied to electrons, no matter what kind of assemblies they form, the law never breaks down.

Here, the electron assembly is the atom. Another atom forms a different assembly. But in all the atoms of a given chemical element the electron families are absolutely identical.

Another Marvel—But as Yet Unexplained

We will have to digress for a moment to talk about the spin of an electron. The meaning of spin will be discussed later on, but one thing has to be said, and that is that spin is incomprehensible from the standpoint of classical physics. The discoverers of spin naïvely believed that it meant the rotation proper of the electron.

The earth revolves about the sun and it also rotates on its axis. The electron revolves round the nucleus and it can also rotate on its axis.

That is clear, isn't it? Now forget it.

Does the electron revolve about the nucleus? Definitely no. The motion of an electron in an atom is much more complicated. To picture it in the 'classical' sense of revolution is to hand out a completely distorted view of actual things.

Does the electron rotate on its axis? Nothing could be farther from the truth. Just try to figure out what the 'axis' of an electron could be. Quantum mechanics views the electron not as a sphere but as a point.* The 'axis' of a point has no meaning. Then add to that the 'rotation' of a point about itself or on itself! That we certainly can't stomach.

The trouble we seem to have got ourselves into now is that there is no way to visualize this spin. True, we never got a very satisfying picture of the particle wave (electron) and the wave particle (photon) either.

The existence of spin in an atomic electron makes itself known from the fact that to the

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* Which is not exactly true either; the reader will have to wait till the next chapter for a better explanation.

angular momentum (moment of momentum) of the electron, which the latter has in its motion in the atom about the atomic nucleus, we add a certain quantity that belongs to the motion proper of the electron. In other words, this quantity has nothing to do with the electron being near the nucleus or far away in a semifree state in a piece of metal, or practically one hundred per cent free in the void of interstellar space. The spin of an electron is always the same and is always associated with the electron.

It appears that the spin of an electron in an atom can either be added to the angular momentum of the electron (which corresponds to electron motion about the nucleus) or subtracted from it. We can express this idea in other words: both values of the total angular momentum of an electron correspond, as it were, to opposite proper motions of the electron, which actually do not in any way differ one from the other. The word 'actually' here has a very exact meaning: both these motions have the same energy in an atom not affected by any external forces.

As a result, each level of allowed energy in the atom may be occupied by two electrons (instead of one) with spins directed in opposite senses.

The Atomic Architect at Work

Now let us take a closer look at the workshop of our atomic architect and his display of blueprints (Fig. 10).

Blueprint No. 1. The hydrogen atom. We pass it up as being too simple, which is funny, seeing that it took science centuries to understand that simplicity.

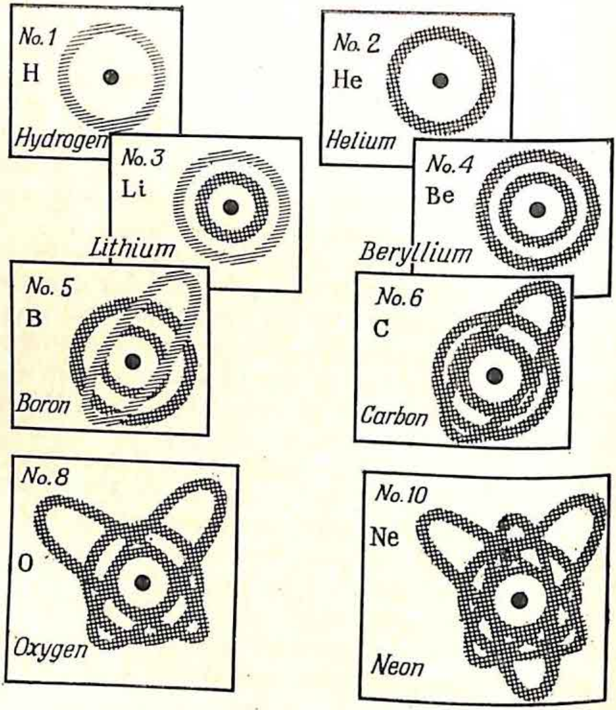

Fig. 10.
Exhibition of projects of an atomic architect

Blueprint No. 2. The helium atom. This one doesn't appear to be very interesting either. We have just found out that each electron cloud may be formed by two electrons. This would suggest that the helium atom is not very different from the hydrogen atom. A model bears this out. The electron cloud is twice as dense and closer to the nucleus, that is all. There are two electrons in place of one.

In the lithium atom (Blueprint No. 3) we notice the formation of a second spherical electron cloud containing within it the first one of helium. Which is natural because the Pauli principle does not allow more than two electrons in one atomic energy 'flat'.

The second tenant in the second-storey flat appears in the atom following lithium—beryllium. So far the atomic house is filling up in orderly fashion.

Now we come to Blueprint No. 5, boron. This was a tough nut for our atomic architect. First of all, he had to save space in the atomic house and so place his new electron tenant so that he would not come into contact very often with the other tenants. Atomic tenants, you recall, don't like each other, they experience mutual repulsion. They all try to move in opposite directions.

The solution of our atomic architect was truly modernistic: he knocked a flat right through all the stories of the atomic house and put the fifth tenant in. Obviously, he was satisfied because in the next blueprint (the carbon atom) he added another tenant to this vertical-like flat.

The following four blueprints don't have anything new. Two new interstorey flats at 120 degrees apart were added to the first one.

That's how nature filled its small atomic house with quarrelsome tenants. The important thing is that they don't fight, which is very essential if the house is to stand. And it must stand.

The meaning of the foregoing is a general principle followed by nature in the construction of atoms. This is a principle of the best distribution of energy.

The mutual repulsion of electrons should greatly increase the potential energy of an atom. But in nature a structure is more stable if the potential energy is low. Falling off a chair is no fun, but on the floor you are more stable, no potential energy.

There is just such a striving towards stability in the world of atoms. The stablest atom is the one with the least possible potential energy. In working out the atomic blueprints, nature spent quite some effort to overcome the mutual antipathies of the electrons by deftly attracting them to the nucleus.

So far the energy principle in atoms has to do only with the intricate internal layout of atomic structures. But that is not all. There is a still more fanciful distribution of living quarters in this atomic building.

Crazy Atoms

So far we have dealt with two basic principles of the structure and filling-in of atomic buildings: the Pauli principle and the principle of best energy distribution.

How does the wave nature of electrons manifest itself? Well, first of all, in place of electron orbits we have charged clouds of probability.

But that is not all. The de Broglie waves in an atom have yet another property. They determine the 'capacity' of atomic structures.

Recall that a feature of electron clouds is that they accommodate a whole number of de Broglie waves. It turns out that this number determines not only the 'number' of the earlier orbit but also the density of the electron cloud formed by all the electrons whose clouds accommodate one and the same number of their de Broglie waves.

To this 'united' electron cloud (we already realize that it consists of a number of pairs of clouds) physicists gave the rather inapt name 'shell'. Quantum mechanics established also the relationship between the capacity of the shell (that is, the largest possible number of electrons that it can accommodate, N) and the serial number of the shell, which is the number of electron waves that fit into it, n. This relationship has a very simple form:

$$N = 2n^2$$

Thus, the first shell (called K) accommodates $2 \times 1^2 = 2$ electrons, the second shell (called L), $2 \times 2^2 = 8$ electrons, the third (M) $2 \times 3^2 = 18$ electrons, the fourth (N), $2 \times 4^2 = 32$ electrons, the fifth (O), $2 \times 5^2 = 50$ electrons, and so forth.

Remember these numbers. Now let us go back to atomic architecture. We see that the first to fill up is the smallest shell of lowest capacity, the K-shell. It is already completely filled in the atom of helium. Actually, this shell is one storey with one flat for two.

The next shell is more complicated. It occupies not only the second storey, but has three interstorey flats, each with two apiece. The

end of the filling comes in the atom of neon (Blueprint No. 10), which occupies the tenth square in the Periodic Table of elements.

The third shell accommodates 18 occupants. It fills up to argon (No. 18) in the same fashion as the preceding shell. The first to fill in is the third storey, and then three interstorey flats. But in the element after argon, potassium, this strict order breaks down.

Here, five interstorey flats have to be filled, but the layout is different. Unlike the first three, these are narrower and more elongated. The new tenant refuses to take up such an inconvenient flat, and demands better living conditions.

Finally the architect puts him in a new flat on the fourth floor. And to keep him comfort, another electron is added in the next atom of calcium.

This certainly is a principle of the best energy distribution. The point is that if an electron takes up residence in the next storey while the lower storey is not yet completely filled, the result is a more stable atom. The potential energy of repulsion of the electrons in such an atom is less.

But then nature goes back to the old system. In nine atoms, from scandium (No. 21) to copper (No. 29), the new tenants are stuck into those long, narrow and uncomfortable flats.

These atoms with flats being taken upstairs and empty flats downstairs have acquired a number of unusual properties. They are called 'anomalous', and will be putting in an appearance now and then.

Strictly speaking, the third shell should fill up completely in the case of nickel (No. 28).

But since nature starts on the next shell before finishing up the preceding one, the third shell is completely filled only in the case of zinc (No. 30).

There is no improvement later on either. A shell doesn't get filled up completely before the succeeding one starts up. What happened in the scandium to copper group is repeated in the group of atoms from yttrium (No. 39) to palladium (No. 46), and from lanthanum (No. 57) to ytterbium (No. 70). From then on, all the atoms right up to the last one (104) have defective, so to speak, tenancy rules, where even two or three shells await lodgers. The next chapter will tell us why they never get their full complement of electrons.

There may seem to be some lack of symmetry here but energy-wise it is the best way.

Thus it appears that the wave law which determines the population and order of settling atomic structures is not all-powerful. This law is frequently modified by a no less important and powerful law of the stability of atomic structures.

Atoms and Chemistry

Let us finish our excursion into the workshop of the atomic architect with a good look at the Periodic Table of elements.

On the left are seven periods, 2 in the first, 8 in the second, 8 again in the third, 18 in the fourth and fifth, 32 in the sixth (these include the rare earths, the lanthanides, at the bottom of the Table), and 17 in the seventh (the reasons for this will, as we have said, be given in the next chapter).

Now let us go back to the figures that describe the capacity of the electron shells: 2, 8, 18, 32, etc. They are the same as in the Table. But then why are some of the numbers repeated: 2, 8, 8, 18, 18, 32 (for the time being we disregard the last period). These repeating numbers, it turns out, are the result of those very breaks in the order in which the electrons fill in the atom. And so the third period ends with argon (No. 18) instead of nickel (No. 28). From then on, this shift (and other shifts due to violations of the filling sequence) continues to the very end of the Periodic Table.

As a result, we don't get an exact and simple correspondence between the shells and the periods. But the capacity of any period does not exceed the capacity of its corresponding shells. Thus the quantum picture gives a good account of one important feature of the Periodic System of elements.

Now take a look at the top of the Table. Here we have Groups from I to VIII and then 0. From school chemistry we would say that they represent valence.

Strictly speaking, this is not exact. First, these are not simply valences, but valences with respect to fluorine (or, as some say, with respect to hydrogen). Secondly, what is valence?

In school we were taught that valence represents the number of atoms that an element.... Today this primitive understanding belongs to descriptive chemistry with its liquids poured into test-tubes and heated on Bunsen burners. Theoretical chemistry has long since received a physical foundation.

Valence—more correctly, valence with respect to fluorine—represents the number of

electrons in the outermost shell of the atom, the one farthest from the nucleus. In this definition, valence coincides with the number of the group, with the exception of the last two columns of the Periodic Table. It would be more correct to put VIII over the last column and the numbers 0, 1 and 2 over the second to the last one. There are some very solid grounds for doing this.

Another question is: Why does the outermost shell of an atom never have more than eight electrons? This immediately becomes clear when we recall the order of distribution of 'living space' in atoms. The first shell accommodates only 2 electrons, the second, 8; the third should have 18, but the build-up stops for a time at argon when there are 8 electrons. After this the outermost shell became number four, and the third shell (now an inner one) begins to fill up. The same happens to the fourth shell, and so on.

As soon as the outer shell has accommodated eight electrons, any further addition of electrons is disadvantageous. But then a new shell appears and the unfilled one goes deeper into the atom. Now we don't care whether it ever gets filled to a complete complement of electrons because only the outermost shell of the atom determines its chemical properties.

Thus there are eight possible types of chemical behaviour of atoms in accord with the number of electrons in their outer shell. Before going any further, it is necessary to point out that a completely filled eight-electron shell has a much smaller potential energy than if it had empty or semiempty 'flats' in it. Which means that an atom with such a shell is extra-stable, chemically stable as well.

Atoms with full outer complements of electrons in their shells are 'noble' to such an extent that they eschew all contacts with the ordinary rank and file atoms. Whence their name: noble, or inert. They make up the last column in the Periodic Table.

The 'aristocrats' of the atomic world move about among the 'common people', who try to copy them in every way. The 'common' atoms make every attempt to fill up their outermost shell to the eight-electron set.

Since they are not able to do that by themselves, they are on the constant look-out for partners. This results in what chemists call a reaction. Really, it is a kind of self-sacrifice: one gives up his attire to the other and remains stark naked. Though not exactly, and what is more, it refers only to atoms that come after neon.

By way of illustration, let us take a reaction between sodium and chlorine, which leads to the formation of sodium chloride, a molecule of NaCl. The sodium atom has an extra single electron in its third shell. The chlorine atom has a handsome set of seven electrons in its outer shell. The sodium graciously sacrifices its sole electron and chlorine then achieves a 'noble' eight-electron outer shell.

But sodium has gained as well. It now exhibits a full complement of eight electrons of the noble gas neon. Two of the 'common people' become two 'aristocrats' at one shot, but only if they go together as a single molecule.

Atoms can, as we see, be divided into givers and takers. Those with less than four electrons in their outer shell are givers. Those with more than four are takers. Naturally, it is easier to acquire two electrons, say, than to give up six

(that, by the way, is the situation in the case of the oxygen atom).

In Group IV we find a number of 'lazy bones'. With four electrons in the outer shell, they don't know what to do, they vacillate.... And they got the name amphoteric, which means partly one and partly the other. These elements are capable of almost any kind of chemical behaviour.

Now in Group VIII we find our 'crazy' atoms. They shouldn't actually be there at all, for they have only one or two electrons at the most in their outer shell. The point is that the underlying shell exerts a substantial and extremely complex effect on the behaviour of the electrons of the outer shell: these atoms are capable of the most unpredictable things. For instance, they have a variable valence, one in one reaction and quite a different one in another. They come in Group VIII simply because their highest valence with respect to oxygen can be 8, which means that each such atom can attach four oxygen atoms to itself.

But don't think that the other 'crazy' atoms hiding in other squares of the Periodic Table behave any better. Not in the least. The tricks they play are just like those of their companions from Group VIII.

Mendeleyev's Table of elements does not reflect this, and one shouldn't expect it to, for the Table was devised at a time when nobody knew how the atom was constructed. Scientists today are not in a hurry to alter the Table for there is still a great deal that we do not understand in the behaviour of the anomalous elements. When everything gets straightened out, then....

The Birth of a Spectrum

Now that we have seen the atom in the new light of quantum mechanics we can learn about how it radiates. We recall that the Bohr theory explained the origin of atomic spectra but could not give a correct description of spectral laws. It was the job of quantum mechanics to fill out the picture in detail.

In accounting for the origin of spectra, quantum mechanics fundamentally agrees with Bohr's theory. In the jumps of atomic electrons from one energy state to another, the difference of these energies is embodied as a quantum of electromagnetic energy, the photon. This is not all, however.

From where to where does the electron jump? As long as there were electron orbits, this was easy to visualize: from one orbit or set of tracks, as it were, to another orbit, another set of tracks. If the energy diminishes, a photon is born. If the energy increases, a photon or a quantum of energy of any other field has been absorbed just before the jump.

But quantum mechanics replaced the orbits with electron clouds. Now it is no easy thing to picture the transition of electrons. We have to conceive it as an instantaneous change in the shape and attitude of the electron cloud in the atom. The emission or absorption of a photon shakes up the atomic 'jelly', producing a new overall form.

Quantum mechanics rejected the pictorial aspect for describing electron jumps, but acquired a new quality, that of probability. In Bohr's theory, an electron jump from orbit to orbit is always possible, and the probability of such a

jump is in no way dependent on the kind of orbit. This is where the theory fails.

Quantum mechanics demonstrates that this is an erroneous conclusion. Electron jumps have a probability that is very appreciably dependent on the shape of the electron clouds that correspond to the electron prior to and after the jump. In this situation, the probability of a jump is, roughly speaking, greater for a stronger overlapping or a deeper interpenetration of these clouds.

Figuratively speaking, an electron can jump into another state like a passenger can cross from one moving train to another when one comes up alongside the other. So, to push the analogy right to the end, the passenger must have energy enough for the jump, the trains must be side by side, the longer the trains (that is, the greater the range of space they will be together) and the closer they are together, the easier it will be for the passenger to make the transition.

Something quite similar occurs in the atom. Here, the 'trains' are in the form of electron clouds, which, we know, can be in diverse shapes, spherical, cigar-like and others.

Studies of the shapes of electron clouds yield rather simple (simple as far as words are concerned) relationships. Two spherical clouds with a common centre (the atomic nucleus) yield a very slight interpenetration; we have every right to say that they don't even come in contact. Which means that there can be no electron jump between the corresponding states. Now put a cigar in a sphere; the thicker and shorter the cigar, the more they interpenetrate. Two cigars can intersect too, but the calculations are more involved. One thing is clear, though,

and that is that the short thick and narrow long cigars interpenetrate to greater depths than the sphere and narrow cigar.

Accordingly, we get the probabilities of electron jumps from a spherical cloud into an elongated one or between two elongated clouds. The laws that divide electron transitions in atoms into more probable and less probable have become known in quantum mechanics as selection rules.

The quantum men have formulated these rules very strictly: some jumps are allowed and others are forbidden, being less probable. But nature does not obey this prohibition.

The selection rules are more or less carefully observed in the light atoms where there are few electrons, so that their clouds intersect rather infrequently. But in the heavy, multi-electron atoms with their terrible confusion of clouds, the restrictions or prohibitions of quantum mechanics largely break down.

It is in this jumping of electrons in the fanciful and rapidly changing tremors of electron clouds that photons are born. The photons enter a spectroscope, get sorted out into types and produce the spectral lines of all the colours of the rainbow. The more photons an atom emits in a second, the brighter the lines.

And if the number of atoms remains constant, the brightness of the spectral lines can depend only on one thing—the frequency of electron jumps in atoms. And this frequency, as we already know, is determined by the probability of jumps. Different clouds have different probabilities, some greater, some practically nil.

To every photon energy and spectral line there corresponds a probability and a bright-

ness. That is how an atomic spectrum consisting of a number of lines of different brightness is generated.

It is easy to describe this in words, but very difficult to calculate the penetration of electron clouds and, on that basis, to compute the probabilities of electron jumps. Yet quantum mechanics solved this problem brilliantly and attained excellent agreement with the observed spectra. The edifice of spectroscopy is now definitely on a granite foundation.

Fat Lines and Double Lines

It would seem that the spectroscope people should now at long last be satisfied. But that's not what happened. The technique of spectral analysis developed rapidly and the instruments became more powerful and sensitive. Then spectroscopists came up with two new queries for the theoreticians.

Does a photon correspond to a line of one frequency, to one wavelength? Yes, but then why do the lines on the photographic plate of a spectroscope come out rather broadened and not slender?

Before quantum mechanics appeared, physicists could have racked their brains over this naïve question for years. Now, only a bit of thinking was necessary. This was due to the wave properties of the electron with their constant attribute, the uncertainty relations.

We have already said that an electron in an atom has a very definite energy. So where do the uncertainties come in? The initial energy is definite, the final energy is also definite; their

difference, which corresponds to the energy of the photon, must also be an absolutely exact quantity!

However, there is a little hitch here. We recall that the exact energy levels refer to stationary states of the electrons (otherwise called steady states) which never change. Now an electron jump is a violation of some steady state. As soon as this occurs, the Heisenberg relation takes over.

What is the lifetime of an electron between jumps? It varies, so let us designate it as Δt. Now from the formula on page 121 we immediately get the uncertainty of photon energy:

$$\Delta E \sim \frac{h}{\Delta t}$$

Whence, using Planck's formula for energy quanta, it is easy to pass on to uncertainty in the frequency of the photon. It turns out to be very simply related to the time of 'settled life' of the electron in the atom:

$$\Delta \omega \sim \frac{1}{\Delta t}$$

In other words, the more 'settled' and quiescent the life of an electron in an atom, the narrower the spectral lines (since these lines refer to transitions to other states), and vice versa. That is why at high temperatures and pressures, when many of the atomic electrons are on the go, the spectral lines broaden out and become smeared.

The second question was connected with the fact that many spectral lines, which it would seem correspond to a single wavelength, actually turned out to be the states of a number of very

closely lying lines. This fine structure of spectral lines was revealed only because of recent advances in spectral techniques.

So electron jumps between the same states could give rise to photons with different (even ever so slightly) energies. So it was only a boast that physicists could give exact determinations of the energy of an electron in an atom.

Physicists rejected this suspicion with indignation, but for this they had to conjure up spin. Spin was discovered precisely because of these 'fine qualities' in spectra.

It turns out that when spectra are generated, the common state of two electrons with opposite spins is not exactly 'common'. It would take us too far afield here to describe the intricate interrelations of the angular momentum and spin of an electron; some of this story will be told later on. But we can say that this is the reason why electrons with different spins have slightly different energies. Whence the doubling of the spectral lines: in place of one line we have twin lines with identical brightnesses.

True, such twins are usually born only when the outer electron shell has one electron. If the number of electrons in this shell increases, we have triplets and quadruplets and even bigger families of the former spectral line. In the atomic world, unlike the human family, this is very common.

That is how quantum mechanics answered two difficult questions of the spectroscope men.

That completes our story about atoms. From now on we will deal with the lives of atomic families—molecules and whole atomic armies in the form of crystals.

Remember how the common atoms tried to imitate the aristocratic atoms of the inert elements. The rich clothes were shared in pairs. At times, three, four and even more partners participated.

From a distance this trick came off all right. A whole molecule was sometimes able to pass through a crowd of atoms just as unperturbed as the atom of an inert element. But at close hand, the cheating was evident.

Instead of atoms, the molecule contains overdressed and underdressed bodies called negative and positive ions. In the redistribution of electron clothes, the atom with garments taken from his partner won't let go of her. And the underdressed companion is not eager to be left alone. This tie-up goes by the scientific term ionic molecule. The adhesive forces in such molecules are mainly the forces of ordinary electric attraction between ions with different charges. So far quantum mechanics has hardly anything to do.

There is a great diversity of ionic molecules. Here, atoms from the left-hand side of the Periodic Table get married to atoms from the right-hand side. The farther away they are in the Table, the more closely knit is the family. And when the atoms come from close-lying groups in the Table, the marriage is not very strong.

But there is just as large a group of molecules whose atoms marry for quite different reasons. The simplest family of this kind is the hydrogen molecule. In this class of molecules, come all the single-element molecules (for instance, mo-

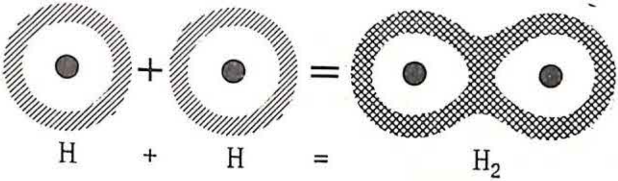

Fig. 11.

lecules of oxygen, nitrogen, chlorine) and also the molecules whose atoms all belong either to the left-hand side or the right-hand side of Mendeleyev's Table. These molecules came to be known as covalent.

Here quantum mechanics had to be called in to account for their existence. Imagine a hydrogen atom coming up to another hydrogen atom. Like the bachelors they are, they envy those who have families, and the first says: "Give me your clothes and we'll form a molecule."

To which the other retorts proudly, "I have just as much right to offer you the same."

"Then maybe we ought to exchange clothes?"

"But where will that get us? Our clothes are exactly the same."

Meanwhile, our atomic architect who has been listening to the conversation steps in with a suggestion (he is now building molecules instead of atoms): "You might as well pool your resources, since you'll never be able to produce an aristocratic eight-electron suit. You haven't got enough material. Let one electron live in one atom for a while, and then in the atom of his partner for a while, and the other can do the same."

"But that won't help," they cry in unison, "we've already proposed exchanging electrons."

"There you're mistaken. You forgot that there will be times when one atom will have the two electrons, and the other won't have any. Then you'll look like two differently charged ions. Whereas in the ionic molecule one atom gives up electrons and the other acquires electrons so that the atoms in it are almost all the time ionized, in your case there will only be an exchange of electrons. First one will be surrounded by electrons and the other will be naked, then the other way around."

"And how often will we have to exchange electrons?" ask the atoms, already giving in.

"Rather frequently," says the architect. "If I used the 'semiclassical' language of Bohr, I'd say about after each orbit the electron of one atom would have to go over to the other. We'd get something like a figure eight."

"All right, let's try," said the atoms.

And the result was a good strong family. It was only quantum mechanics that could figure out this legerdemaine of nature. Quite rightly, the quantum men called this interaction of identical atoms that lead to the formation of molecules 'exchange interaction'. Classical physics would never have been able to think up anything like that.

Here's how quantum mechanics pictures this exchange of electrons. As long as the atoms are some distance apart, their electron clouds hardly at all overlap. But when these atoms come close enough, the considerable mutual interpenetration of the electron clouds make perceptible the probability of an electron of each of the atoms finding itself near the nucleus of the partner

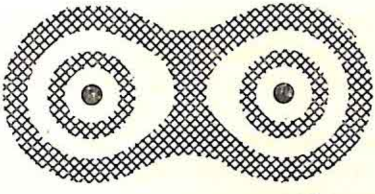

Fig. 12.

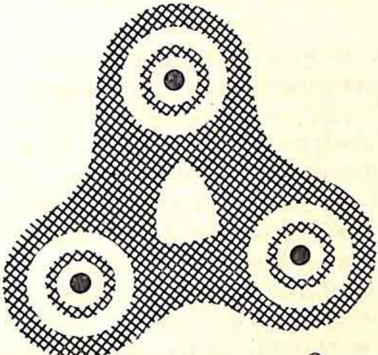

Fig. 13.

atom, which amounts to a probability of exchange.

What is this probability? About 15 per cent for the hydrogen molecule. Put otherwise, during 10 minutes of each hour both electrons come together in a single atom of hydrogen, while the other atom has none.

Is this enough to bond the atoms firmly into a molecule? It is, say the calculations carried

out by the English scientists Heitler and London by means of quantum mechanics. True enough, the theory here is in excellent agreement with experiment.

In the world of molecules, this teaming up of 'rich' and 'poor' atoms via exchange of electrons is very common.

For example, the nitrogen atom (No. 7) has only seven electrons. Two in the inner shell do not participate in exchange actions. But in the outer shells 5 electrons are married off to other atoms.

The next atom following nitrogen is oxygen, which has six electrons for exchange purposes in each atom. These form a molecule of ordinary two-atomic oxygen (Fig. 12). In three-atomic oxygen (ozone), a union of 18 electrons is formed. And to simplify the exchange, the three form a triangle to cut down the distance the electrons have to cover. These three atoms toss their electrons about like a ring of players in volleyball practice (Fig. 13).

This molecular structure no longer resembles the architecture of the constituent atoms. And the flats together with the distribution of tenants differ too. All of which makes the properties of molecules quite different from those of the atoms they are made up of.

Solid Bodies are Really Solid!

A turn of the path brings us to a new landscape, one which we are most accustomed to: the solid things everywhere about us. Familiar things all, but possessing secrets and mysteries that still flout science.

By the turn of the century, physics had already accumulated considerable material on the properties of solids. We know that solids come in crystalline and amorphous form, that they conduct heat and electricity in a variety of ways, and the transmission of light and sound is different too. Yet solid-state physics, as it is called, has great difficulty in accounting for any of these properties.

Yet this is very important, for rapidly advancing technologies are making use of new natural materials. The demands are so great that artificial materials are pressed into service.

We need materials that possess great hardness, electrical conductivity, heat resistance and many other properties. Where do we get them? One way is by combining all known materials and familiar methods of working them, a sort of alchemistry. There is another way but it requires the use of quantum mechanics.

Again, in just a few years, a breakthrough. In the beginning, the attempt was made to comprehend the structure of crystals, primarily the crystals of metals.

Crystals are indeed the best thing to start with. A crystal is an ordered periodic distribution of atoms in space in a lattice-like configuration. Unlike the ordinary lattice with its two dimensions, this one has three dimensions. In a lattice, the atoms of the crystal are located at constant distances: this is called lattice spacing. In the general case, there are three spacings in accord with the three dimensions of the lattice: length, width and height.

Pure elements are not common in nature, we more often encounter their compounds. The lattices of such crystals are made up of several

types of atoms. A simple case is the ice crystal which has hydrogen and oxygen atoms; here, in accord with the formula for water, the number of hydrogen atoms is twice that of oxygen atoms.

Another case is the lattice of crystals of sodium chloride, NaCl. At the intersections of the elements of the lattice (called nodes) we find ions of sodium that alternate with ions of chlorine. Note that these are ions and not atoms. It is very important that when molecules of salt 'freeze into' a solid body the ionic nature of their atomic bonds is retained.

But as such the molecule ceases to exist. It cannot be isolated. Indeed, each sodium ion is surrounded by ions of chlorine, and each chlorine ion is surrounded by sodium ions. Go and try to find the old molecule!

In a crystal like this, the forces acting between ions are ordinary electrical forces. A sodium ion attracts chlorine ions in the immediate vicinity, those in turn attract other sodium ions, but repulse adjacent chlorine ions. The result of this interplay of forces of attraction and repulsion is a certain equilibrium in the ion configuration. This is the crystal lattice.

This arrangement is indeed in equilibrium and stable. If one ion gets knocked out of position, its attractive force towards ions of a different kind is diminished, but its own ions repulse it more strongly. The combined action of these forces compel the ion to return to its original position.

Strictly speaking, an ion is all the time in oscillation about its stable position due to the random knocks of thermal motion, like a sphere attached to a system of springs. The thermal

vibrations of ions in a lattice determine many important properties of solids.

And as in the case of ionic molecules, quantum mechanics hasn't much to do with ionic crystals. But then physics turns to metallic crystals, the most important in modern technology.

Here the situation is quite different. Suppose that the entire lattice is made up of a single metal, that is, of atoms of one kind. Quite naturally there will be no difference in the charge of the ions. If one atom readily gives up an electron, why shouldn't all the rest do the same?

Maybe that is the case? Quantum mechanics recalls the recent victory over the hydrogen molecule. What if the metallic crystal is indeed a gigantic covalent molecule consisting of many millions upon millions upon millions of atoms?

This ingenious idea proved correct. Nature was not so inventive and didn't come up with anything. The trick with electron exchange between two atoms came off right and so nature extended the experiment to more numerous electron assemblies.

Still and all, it is indeed not so easy and simple. Solid bodies will have opportunities enough to show that they are tough nuts to crack, even for quantum mechanics.

Skeletons and Multistorey Structures of Crystals

When the atoms of metals join to form crystals, they do actually make their outermost (valence) electrons common to all. This results in a sort of skeleton architecture of the crystals. At the lattice nodes are slow-moving ions surrounded by a light and mobile common cloud of

electrons. This cloud plays the part of cement holding together the hostile similarly charged ions. In turn, the ions are the adhesive that keeps the electrons from flying off in all directions.

We have already had occasion to say that the electrons in a metal are 'almost' free. Since every atom makes its contribution to the common weal, each electron ceases to belong to some one atom and is simply one of the millions upon millions upon millions of other servants of all the atoms. Such an electron is free to wander anywhere about in the crystal, a microscopic Figaro.

True, not all electrons are so free. Each of the atoms gives up only one or two of its outermost electrons, the rest are held firmly in place within the atom. Even so the army of free electrons is colossal: 10^{22} to 10^{23} in every cubic centimetre of metal.

If one may say so, a metallic crystal has a better 'social' organization than an ionic crystal, where we find something like slavery with all the electrons chained in their atoms. Metal is closer to feudalism: the owner lets his serfs out a bit to earn rent. This improvement immediately gave the metal new properties and the opportunity to conduct electric current.

If an ordinary electric field is applied to an ionic crystal, there will only be a slight redistribution with the electron clouds in their atoms somewhat elongated. This will result in what is known as electric polarization of the crystal. Not a single electron will get away from its ion, and the ions themselves will, as before, remain firmly anchored at their nodes. And since there are no free carriers of charge, there will be no electric current. Ionic crystals are insulators.

Now in metals there are simply oodles of electrons ready to carry charges and produce a good electric current.

But where do the semiconductors come in? We'll find a place for them a little later on.

For the present we shall examine an important fact which was established by quantum mechanics for metals. The question is: What kind of energies do the 'collective-like' electrons in the metal have? The answer is simple: electrons no longer tied to their atoms should, it would seem, be able to have all kinds of energy. As we recall, in the case of free electrons the quantum nature of their energy levels disappears.

But let's not hurry with this conclusion. True, the electrons have left their atoms, but they haven't left the piece of metal. They no longer obey atomic laws but there are general rules for the metal as a whole that govern the behaviour not of some one electron but of the whole electronic ensemble.

About these laws. You recall that the atomic laws were found from solving Schrödinger's equation. So in the search for the rules of conduct of electrons in a metal (metallic crystals) physicists did the same. They solved the Schrödinger equation for electron motion in a periodic electric field of positive ions spaced at regular intervals at the nodes of the crystal lattice of a metal.

A slight digression is in place here. Up till now, when speaking of the effect of one atom on another close by, we have always had in view the external, as it were, manifestations. Atoms attracted one another and formed molecules.

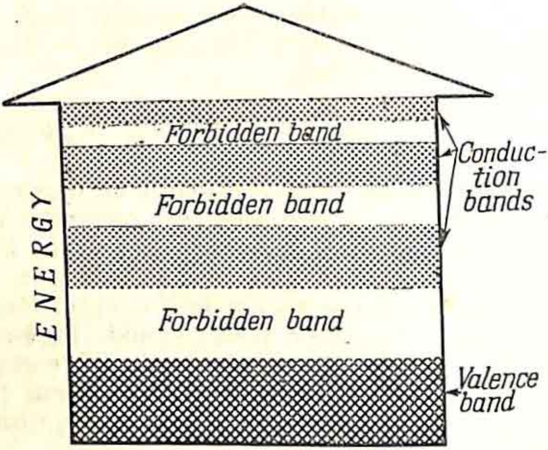

Fig. 14.

But what, meanwhile, is happening inside the atoms themselves? It turns out that the electron clouds alter their configurations. This was discovered by the German physicist Stark before quantum mechanics had fully developed. Stark found that when a strong electric field is applied to a substance, the lines in the emission spectrum are split.

This splitting has nothing at all to do with the twin lines we discussed earlier. Yet there is something in common, which was demonstrated by quantum mechanics. The splitting of spectral lines corresponds to a splitting in the energy levels of the atomic electrons.

To summarize, then, an electric field applied to an atom breaks up the energy levels of its electrons. The action of the electric field of an

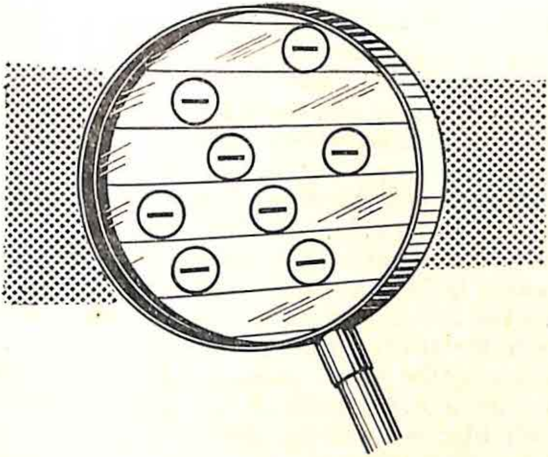

Fig. 15.

atom that has approached close enough to another atom (the field in this case is quite substantial) does not differ in any essential respects from what we have described.

True enough, when a molecule is formed, the energy levels corresponding to the constituent atoms disappear. They break up, intermix, and shift up and down the energy scale to produce so-called molecular levels of energy, which now correspond to the entire molecule.

But what relates to a molecule is more clearly expressed for a crystal where there are so many atoms packed close together repeating this packing throughout the crystal. Actually, a crystal is simply a gigantic 'frozen' molecule.

The joint electric field of all the atoms of this 'molecule' splits up the energy levels of

each one of them into an enormous number of very closely lying sublevels. The discreteness and distinctness of the permitted energy levels of the outer electrons vanish almost completely. It would seem therefore that an electron in a crystal can have any energy it wishes.

Then a remarkable thing happened. Take a look at the drawing (Fig. 14). The conclusion we have just drawn about an electron having any energy it wants is fulfilled, but with one very essential exception. The blank bands indicate energies which electrons in a metal cannot have. To these energies there corresponds a zero wave function and, accordingly, a zero probability of an electron finding itself in such a state. These blank white bands of energy were termed forbidden zones, or bands.

And even in the cross-hatched, so-called permitted bands, an electron is not allowed to have just any energy. If we could reproduce the actual picture on paper, we would see that there are separate energy levels in these bands as well. But each band has so many of them (recall the stupendous numbers of electrons in every cubic centimetre of metal) that they simply merge into a continuous sequence.

Now about how the electrons reside on these levels. Not any which way, like birds on wires. The Pauli principle doesn't allow that. This strict inspector watches just as carefully in the metal as he does in the atom. Only two electrons are allowed on each energy level of the permitted zone of a metal, states the Pauli principle. There is plenty of place, and more than enough levels of energy. There is always a lot of extra 'living space' in a metal. Under normal conditions, all the electrons of a metal

can settle in the lowest permitted zone, on the ground floor.

Under this is a 'basement', as it were, with all the noncollectivized electrons which belong to the individual atoms and not to the atoms of the metal as a whole. The basement is not insulated air-tight from the ground floor, there is a ladder between them. It consists of a single rung equal in height to the first forbidden band. If knocked hard enough, an electron can be boosted from the basement to the ground floor. But it is not allowed to get stuck in the forbidden band due to lack of energy.

To the energy basement physicists gave the name valence zone, or valence band. And all the allowed bands of energy are called by the generic name conduction bands. The origin of these terms is clear: the basement is inhabited by some of the outer electrons that determine the valence (though these electrons are not yet free), while the ground floor and the upper stories are inhabited by electrons that participate in the conduction of electricity.

Insulators Can Conduct Current!

Insulators, of course, keep all their electrons in the basement. Under ordinary conditions, their conduction band is empty, the first forbidden band is too broad for any of the electrons to find the energy needed to jump across it. But when the insulator is heated properly, the energy of oscillations of its ions at the lattice nodes becomes very great. This energy can be imparted to the electrons and these occasionally become energetic enough to jump up into the

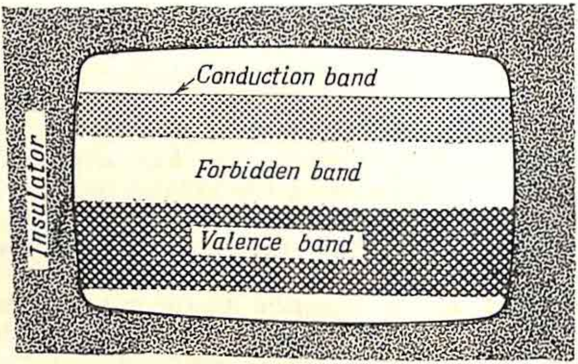

Fig. 16.

conduction band. The insulator then begins to conduct current. This is called heat breakdown.

Actually, to account for this breakdown we don't need quantum mechanics, for it only means that the electron has broken out of its narrow atomic world and has got into the conduction band and become practically a free man. The energy required for its release was simply equal to the width of the forbidden band separating the basement from the ground floor.

All this can be pictured as follows: a thermal 'knock' ejected the electron from its atom, ionizing the latter, while the electron released from its atom is now moving freely but is not yet able to leave the chunk of insulator.

But it turns out that an insulator also becomes a conductor of electricity when a very strong electric field is applied to it. Wait a minute, isn't this just like the cold emission of electrons from a metal that we discussed in the previous

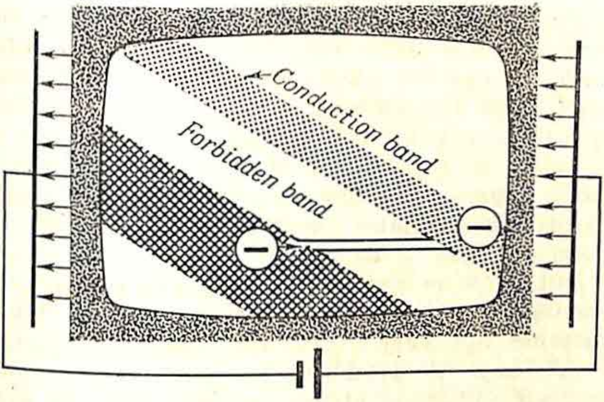

Fig. 17.

chapter? But this isn't a metal, it's an ionic crystal! There, the electrons escaped the metal altogether, whereas here they only jump from the valence band to the conduction band.

Still, despite the differences, this is one and the same phenomenon. The miracle in both instances is the tunnel effect. Indeed, what is a forbidden zone if it isn't a potential barrier? Yes, it is simply a potential barrier of practically infinite (for the electrons, naturally) width. It's simply a step with only one 'front' side. An electric field, as before, bends it and creates a 'rear' side. As a result, the barrier now has a finite width.

The rest is all the same. The electrons begin to seep through from the valence band across the barrier into the conduction band. First we get a small electric current; the probability of penetration is low and few electrons get into the conduction band. But this current, as it

moves through the crystal, heats it like the wire in a hot-plate. This heating, in turn, adds fresh armies of electrons to the conduction band, and the current in the insulator builds up of its own accord. In just no time there is an electric rupture of the insulator. This is accompanied by a simultaneous thermal breakdown—the insulator melts. It is no good any more and has to be thrown out.

But there is a more peaceable manner of generating electric currents in insulators. These currents are very weak and absolutely harmless. They are produced by illuminating ionic crystals. Photons strike the crystal, knocking electrons from the valence band into the conduction band. This is a real photoelectric effect, but there is no emission, it all takes place inside, so to speak. There is no harm done, and at the same time it is just the thing for practical applications.

How does Current Move in a Metal?

In this twentieth century, one seems ashamed even to ask a question like that. Don't electrons leave a source of current, move along a wire driven by an electric field and enter the current source again, like water pumped into a pipe?

Yet we are not ashamed. Where does electric resistance come from? A conductor is not a pipe, the walls are not rough. Why does a metal filled with so many current carriers offer resistance to the flow of current?

This is one of those naïve questions whose answer is far from simple. Electric currents

have been known for a hundred and fifty years, while the answer to our query came to light only about thirty years ago.

Here is how classical physics explained electrical resistance. The directed movement of electrons—what we call current—is all the time upset by the thermal vibrations of ions in the skeleton of the metal. These vibrations impede the motion of electrons. Electrons begin to move like people in a building during an earthquake—walls and floors rising and falling and swinging and shaking.

Obviously, the smaller the vibrations of walls and floors, the easier it is to walk about the building. At the absolute zero of temperature, when the thermal vibrations of the ions cease altogether, electrical resistance should drop to zero. Which is very close to the truth as regards very pure metals almost devoid of impurities. The whole trouble lies with these impurities. As the temperature falls, the resistance of such 'dirty' metals does not tend to zero, but rather to some nonzero value which depends on the content and type of impurities in the metal. The more impurities there are, the higher this residual resistance.

What does classical physics have to say on this score? Just nothing. It doesn't distinguish an atom of the metal from an atom of impurity: at the same temperature they vibrate in the same manner and impede the electron motion in exactly the same way.

Now quantum mechanics proved a little more observant. These different atoms in the lattice are distinguished very clearly, almost as if they were of different colours. Then how do we account for the electrical resistance?

First we'll have to recall the elegant experiment dealing with electron diffraction on a crystal that we started our talk with about quantum mechanics. There the electrons which impinged on the outer layers of the atoms of the crystal were partially reflected and formed diffraction rings on a photographic plate.

Couldn't we consider the electron current in a metal as a beam of electrons? Well, yes. Here the electrons stream along in one general direction, only the beam is wider occupying the whole cross-section of the piece of metal. But then it inevitably follows that the passage of electrons in a metal should be accompanied by an 'internal diffraction', as it were, of electrons on the ions of the lattice. If we could put a photographic plate inside the metal, we should be able to get a diffraction pattern.

Diffraction has an interesting property: if there is the slightest deviation in the regularity of the objects scattering the waves, the clear-cut pattern vanishes and the plate is uniformly fogged. As physicists say, the scattering of the waves has become homogeneous.

It is just such disorder that is introduced into the regular structure of a metallic crystal by ionic vibrations and by the presence of impurity atoms. As a result, the waves of the electrons participating in the current are scattered in all directions.

As a rule, the impurity atoms have quite different dimensions and electron shells than the atoms of the metal. The impurity atoms distort the lattice. Pushing the analogy further still, we could say that the impurity atoms twist the corridors, bend the walls and deform the floor of our building. It is clear that these de-

fects remain even when the floor and walls cease to tremble. Sure enough, the distortions introduced into a metallic lattice by impurity atoms are independent of the temperature and remain even at absolute zero. The scattering of electron waves on these lattice imperfections is the cause of the residual electric resistance of metals that was so incomprehensible to classical physics.

Thus, it turns out that metals are far from perfect as conductors of current. True, not all of them and not at all times. Nature, feeling that it just had to produce something better, created superconductors.

A number of metals and alloys (as yet, just a few) begin to behave very strangely at extremely low temperatures. At just ten or so degrees above absolute zero, these substances suddenly lose practically all their electrical resistance. This phenomenon, discovered half a century ago, became known as superconductivity.

Classical physics could not find an explanation for it. It is interesting to note that even the powerful quantum mechanics had to work hard for about thirty years before it came up with anything reasonable.

The enigma of superconductivity was resolved only a few years ago. A big contribution to disentangling this mystery was made by the Soviet physicist N. N. Bogolyubov and his pupils. To talk about superconductivity any more would take us too far afield. We shall confine ourselves to a brief and rather crude but pictorial analogy.

The superconductivity trick is due to the fact that at very low temperatures close to absolute zero the interaction of the electron cloud with the ionic skeleton in a number of metals changes drastically due to certain peculiarities of struc-

ture. Whereas before, each soldier of the electron army fought on his own, at the low temperature of superconductivity the electrons form into pairs.

The effect on the war between the electrons and ions is immediate. Whereas before, each electron fought separately with the ions and could easily be put out of commission, now these electron teams warded off the blows of individual ions without batting an eyelash. The electrons ceased to notice the aggressive ionic encirclement, as it were. The difficulties of the electron army were reduced, and finally the electrical resistance of the metal fell off catastrophically.

In the language of physics, the new type of war consists in the fact that now the wavelengths corresponding to electron motion in the metal are of an order of magnitude thousands and tens of thousands of times greater than the distances between ions. The secret of these new tactics is quite obvious if you have read this chapter with care: the wavelength of an electron pair is so much greater than the dimensions of the ionic obstacles in its path that the scattering of individual electrons, which accompanies the passage of current through a metal under ordinary conditions, disappears—and with it, the resistance to current.

This ideal organization of the electron army is maintained only so long as the temperature is sufficiently low. As the temperature rises above a certain limit, the clashes with ions break up the pairs into separate soldiers. The balance of forces has changed and the electrical resistance of the metal is restored.

So it was worth asking how current flows in metals.

Those Wonderful 'Semi-Things'

You've probably already guessed what these semi's are about. In nature, a great number of things belong neither to conductors of electric current nor to insulators, but to semiconductors.

Their semi- or intermediate properties have proved so valuable that semiconductors, which made their appearance just a few decades ago, have wrought a real technological revolution. The properties they possess are rather well known: unlike insulators, semiconductors conduct current at room temperature, and unlike conductors, their electrical resistance does not increase with temperature, but falls off.

Nature did make a sharp dividing line between insulators, semiconductors and conductors. Actually, we already know the gap that lies between them. It is the first forbidden band between the electron-filled valence band and the conduction band with its numerous unoccupied electron states.

In insulators, a great deal of energy is needed for an electron to climb out of the basement into the ground floor because the step is high. This energy may be obtained only at high temperatures (recall thermal rupture).

In semiconductors this step is much smaller. The energy the electrons require to make their way up into the ground floor is now obtainable at room temperatures. That is why semiconductors begin to conduct current at ordinary temperatures.

In other words, when even a weak electric field is applied to a semiconductor, a directed flow of electrons is set up in the conduction band. Now let us see what is happening in the basement.

Things are developing there too. The point is that when an electron moves out of the basement into the ground floor it leaves behind a vacant room. The densely populated basement immediately begins a redivision of living quarters. Now only one electron is permitted to move into the room; this is straightway done by one of the electrons close at hand. But it in turn leaves behind an empty room, which again, in turn, is occupied by a fresh electron.

In jumping from room to room, these basement electrons imitate the freely moving electron on the ground floor. Something like a kangaroo copying a human runner. The runner takes small and fast jumps, but from a distance it looks as if he were smoothly building up speed; the kangaroo takes only a few long jumps.

If we take it that the first electron room was vacated in the centre of the city, the resettlement of electrons results in the room moving out to the city limits.

This travelling electron room was given the rather derogatory name of 'hole'. Its behaviour is just the converse of that of the electron which left the hole—in an electric field it moves in the opposite direction, like a positively charged particle. Another difference is that it moves in slower and larger jumps.

At low temperatures all the electrons are securely trapped in the basement. As the temperature rises, however, more and more of them are released, the current increases and the resistance of the semiconductor diminishes—it is just the other way around for a metal conductor.

So far we have been talking about pure semiconductors. The current mechanism here is called

intrinsic conductivity. Pure semiconductors, however, are of little interest to technologists. All the marvels that semiconductors are capable of come with what are called impurities.

Useful 'Dirt'

Dirt, impurity—it's bad when it's accidental but it's really very good in definite proportions. Semiconductors are no exception to the general run of things, they get 'dirty' too. All kinds of impurities get into their crystals, but these are accidental and unwanted. Now there are some impurities that are very useful—when applied in strictly regulated doses. They are the ones that produce the marvels.

What is sauce for the goose is not always sauce for the gander. If you want a metal with a high electrical conductivity, all impurities are detrimental. And we already know the reason: impurity atoms get into the crystal lattice and distort it. These distortions, or imperfections, scatter the waves of the electrons carrying the current. As a result, the electrical conductivity of the metal decreases, and the resistance increases.

Yet these very lattice imperfections are the key to the success of semiconductors. The fact of the matter is that the structure of the energy bands of a crystal is exceedingly sensitive to the type of crystal lattice. Every crystal has its own system of energy bands.

However, impurity atoms do not alter the shape of the entire lattice but only in their immediate vicinity. The band pattern common to the whole crystal is appreciably modified in these

areas. What happens is this: additional allowed electron-energy levels appear in the forbidden band that separates the valence band from the conduction band. These levels originate only where there are impurity atoms. To distinguish them from levels existing in the whole crystal of the semiconductor, they are called local levels.

The amount of impurities in a metal also affects the conductivity, but always in only one direction—the more impurities, the lower the conductivity. And the range of variation is relatively small. Now in semiconductors, the electrical conductivity may be varied not only by the number of impurity atoms but also by the type of impurity atom, and the changes may be thousandfold and millionfold!

Generous and Greedy Atoms

The most common impurity semiconductors are presently based on the chemical elements of germanium and silicon. Take a look at the Periodic Table of elements: silicon is No. 14 and germanium, No. 32. They are in the fourth group. You remember what we called this group? Something intermediate. And that is exactly what it is. Germanium and silicon are neither conductors nor insulators, they are typical semiconductors.

The outermost shell of either atom contains four electrons. When the atoms are brought into a crystal, all these electrons go to form bonds with other atoms. They are slaves in the basement. And so at low temperatures, silicon and germanium do not conduct current.

But let us add to germanium a bit of one of the neighbouring atoms, say arsenic (No. 33) of the fifth group. In places, the arsenic atoms will dislodge the germanium atoms and occupy their places in the lattice. In doing so, each arsenic atom will have to do the job of the displaced atom of germanium.

An atom of arsenic has five electrons in the outer shell. Four of these he gives up to take care of the chemical bonds of the guy whose place he took in the lattice—the germanium atom. Now the fifth electron is left unemployed.

Calculations show that the energy of this electron exactly corresponds to the local level in the forbidden band, but near the limit. Only a very little energy is needed to push this electron into the conduction band—10 to 15 times less than the height of the forbidden band itself.

The arsenic atom, which was so generous with its extra electron and gave it to the crystal host, is called a donor. And the respective electron levels are called donor levels (Fig. 19).

Now let us take, in place of arsenic, some element from the group to the left of germanium, let us say, boron (No. 5). Boron is in Group III, which means that its outer shell has only three electrons. When boron takes the place of a germanium atom in the crystal lattice, it can handle only three of the four chemical bonds.

Here's what happens. The boron atom steals an electron from a neighbouring germanium atom. This is contagious. The atom of germanium then grabs an electron from a close-lying neighbour, who does the same. This unoccupied electron room begins to move farther and farther away from the germanium atom that first stole from his neighbour (Fig. 20).

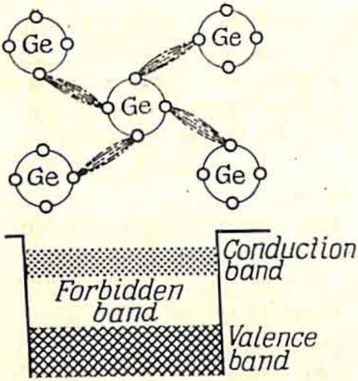

Fig. 18.

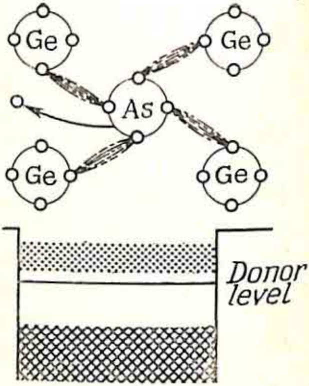

Fig. 19.

This is a familiar picture, exactly like the migrating hole. The only difference is that here it is not temperature that ejects the electron from the valence band, but the presence of an atom of boron.

In the process, we again find the formation of local energy levels in the forbidden band near the bottom. And the difference is that holes, not electrons, can occupy them.

These atoms, like the thief boron, came to be called acceptors. The corresponding hole levels are known as acceptor levels (see Fig. 20).

Hence we have two types of electrical conductivity—by electrons or by holes—in accord with the type of atom that settles in the lattice of germanium or silicon.

We again ask the reader to bear in mind that a hole is simply a convenient convention to designate electron motion. If you want to, picture

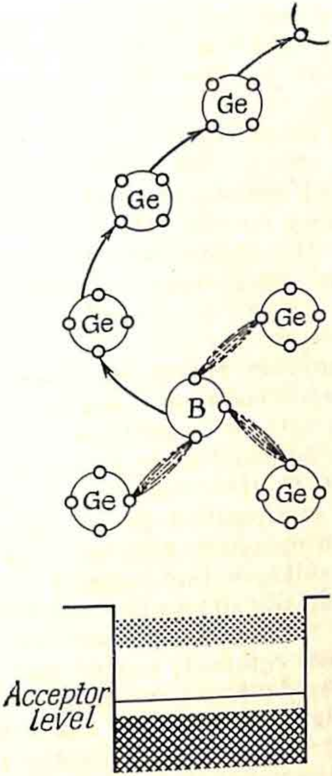

Fig. 20.

the hole as an electron jumping kangaroo-like from atom to atom in the filled valence band. Then an electron in the conduction band will be more like a smoothly moving human runner, taking fast small steps. We have already said

that the electron levels in the conduction band are also separated one from the other, but that these distances between levels are so insignificant that the levels actually merge.

Returning to our story, let us try mixing boron and arsenic atoms with germanium. What conductivity will germanium have? This will obviously depend on the ratio of the number of atoms of the two impurities. If there is more arsenic, the conduction will be electronic, if the other way around, it will be hole conduction.

All this mixing makes for important applications of semiconductors. Semiconductors with such double sets of impurities are capable of stopping the flow of current in one direction and of passing it in the opposite direction. Which means that semiconductors are rectifiers.

Another thing semiconductors can do is convert small voltages into large voltages (again due to their ability to regulate resistance). Which means that they can operate as amplifiers.

These small, compact, rugged and economical semiconductor devices have long since won out over the big, cumbersome electronic valves.

Photons striking a semiconductor knock electrons from the valence band into the conduction band. When illuminated, a semiconductor in a circuit begins to conduct current. Which means that semiconductors are capable of transforming light energy directly into electric energy. What is more, they are already doing that and doing it more effectively than metals.

Pioneering work in this field was done by the Soviet physicist A. Ioffe and his colleagues.

Silicon batteries in desert areas convert the blistering streams of solar rays into electricity,

which drives motors in irrigation systems to bring water to thirsty corners of the earth. Semiconductor electric batteries have found applications in space exploration.

Semiconductors also convert thermal energy directly into electricity. No longer needed are the unwieldy systems of steam power stations where heat first converts water into steam, and then the steam drives a turbine connected to the rotor of a dynamo. This is already obsolete and will disappear some day altogether. Meanwhile semiconductors are working as thermoelectric generators, converting the heat of kerosene lamps into electricity and as refrigerators with no moving parts.

That is only the beginning. Ahead lies a brilliant future for these marvellous little crystals.

The Interior of the Atomic Nucleus

On the Threshold

Atoms, molecules, crystals, now what?

Quantum mechanics will now take us on a trip deep into the interior of the atomic nucleus itself. There are still marvels to be uncovered.

In the twenties, no one could even imagine what this would lead to, the physicist was simply curious. The atomic nucleus had much to offer. At that time, quantum mechanics was celebrating its first victories in atomic combat, and hardly anything at all was known about the deep inner core of the atom.

We shall begin with what little was known at that time. At the very end of the nineteenth century, the Frenchman Becquerel quite accidentally noticed that some substances are capable of clouding a photographic plate. Following up this discovery, Marie Sklodowska and Pierre Curie found that this property is possessed by three chemical elements at the end of the Periodic Table—radium, polonium and uranium.

This phenomenon was called radioactivity. Theoreticians in those days were very embarrassed by the fact that classical physics could not

account for radioactivity. Meanwhile fresh facts about the mysterious radiation were accumulated. There were, it turned out, three kinds of radiation: alpha, beta and gamma rays.

Further studies demonstrated that alpha rays consist of positively charged particles. An alpha particle had a charge double that of the electron, while the mass was roughly four times that of the hydrogen atom. Beta rays were undistinguishable from electrons. Gamma rays were, as the physicists said, extremely hard electromagnetic radiation, with a penetrating capacity many times that of the record-holder X-rays.

Another few years passed and the English physicist Rutherford working together with his pupil Bohr expounded the planetary model of the atom in which electrons, like planets, revolve about their central 'sun', the atomic nucleus. It gradually became clear that the generator of radioactivity was the nucleus.

With respect to the alpha particles, this was obvious from the very start: there is no place in the atom for them except the nucleus, which contains practically the entire mass of the atom. On the other hand, electrons exist in the outer atomic shells. We also frequently find photons (quanta of electromagnetic energy) flying out of these shells. Maybe beta and gamma rays originate in the electromagnetic structure of the atom.

No, this is clearly impossible. When an atom emits beta rays it does not become ionized, it does not acquire an electric charge. Which means that its electronic structure remains unchanged. Further calculations of energy corresponding to photons of visible light and X-rays associated with jumps in electron shells demonstrated that

this energy is only a fraction of the photon energy of gamma rays. Again, this was support for the idea that these two types of radioactive radiation originate in the atomic nucleus.

Several years passed and Rutherford gave theoretical physicists some more food for thought. In the pathway of alpha rays emitted by radium he put nitrogen nuclei, and photographic plates that recorded collisions of alpha particles with nitrogen nuclei exhibited traces of ... oxygen nuclei! The dream of the alchemist come true: a transformation of chemical elements had taken place, though not in chemical fashion.

That same year, Rutherford observed the first nuclear transformation and found that the nuclei of atoms of a single chemical element can have different masses. Calculations showed that these masses differed by an amount that was a multiple of, or very close to, the mass of an atom of hydrogen. Such nuclei became known as isotopes.

The First Step

Radioactivity and the transformation of nuclei, then isotopes. Surely it is now time to take the first step in constructing a theory of the atomic nucleus. The starting facts are here and we have quantum mechanics, which has already proved its worth.

But the theoreticians were not in a hurry. They continued to stand on the outskirts of the primordial forest listening to its murmurings and partaking of its odours, but they feared to enter. They were not ready to subject their new-born child, quantum mechanics, to the rigours of new environments.

What they asked of experimentalists was to break a path into the forest. Which they were not long in doing: in 1932, the Englishman Chadwick discovered the neutron. Now they could start.

One basic thing was not clear: What particles did the nucleus of the atom consist of? The fact that it was a composite nucleus was obvious, for we had radioactivity—particles flying out of the nucleus and the nucleus continuing to exist. Incidentally, one nuclear particle, the proton, was definitely established.

We could now surmise that the nucleus consisted of those particles that appear in radioactive disintegration: alpha particles and electrons. But this is too simple a conjecture. Alpha particles seemed to have the same properties as helium nuclei. Yet there were still lighter nuclei, those of hydrogen. Thus, the hydrogen nucleus should be the smallest building stone in the nuclear edifice. Since this was the most elementary particle, it got the Greek name proton.

Now we can begin building our model of the nucleus. We must take into account the basic rule—the charge of the nucleus must be equal to the collective charge of all the electrons in the outer structure, but with opposite sign (positive). Otherwise the atom would not be neutral the way it is. We also know the nuclear masses: they are roughly equal to the masses of the corresponding atoms minus the masses of their electronic shells.

So we have our starting hypothesis: nuclei consist of protons and electrons. The nucleus of hydrogen has one proton, and there are no electrons at all. The helium nucleus has four protons and two electrons; its charge is thus $+4-2=+2$,

its mass is just a little bit more than four times the hydrogen nuclear mass. We know that the electron is almost 'weightless' compared to the proton—nearly 2,000 times lighter!

We continue. The lithium nucleus with mass 7 and charge +3 consists of 7 protons and 4 electrons, the boron nucleus with mass 11 and charge +5 consists of 11 protons and 6 electrons, nitrogen (14 and +7, respectively) consists of 14 protons and 7 electrons; oxygen (16 and +8) consists of 16 protons and 8 electrons, and so forth.

Everything seems to be going normally. But it only 'seems' that way. As long as we confine our building activities to the light nuclei, everything is all right. But as soon as we move into the region of medium and large structures, agreement breaks down. Judge for yourself. Iron with nuclear mass 56 (this is more correctly called the mass number of the nucleus; it shows how many times the mass of the nucleus is greater than the mass of a proton) and charge +26 requires 56 protons and 30 electrons; for the uranium nucleus with mass number 238 and charge +92, we must have 238 protons and 146 electrons.

It turns out that to each new nucleus nature adds several protons, not one, as might be expected. If, however, we reject this view, then trouble sets in with the nuclear masses and charges. As a result, our regularity in nuclear construction breaks down. Then there is difficulty in figuring out where isotopes come from. Trouble with nuclear spins too sets in from the very start. Their total spin must be equal to the sum of the spins of the constituent particles. For example, for the nucleus of heavy hydrogen (deuterium) which is generated via this scheme by two protons

and one electron, the total spin should at leas- be equal to three proton spins (proton and elect tron spins are equal). Actually, it is equal to two proton spins! And this is not the only discrepancy. Quite the contrary, coincidence of calculated (by this scheme) and measured nuclear spins is very rare. There must be something wrong in our method of building nuclei.

Sure enough! The nuclear electrons have the job of building up the charge of the nucleus so that it corresponds to the experimentally observed value. But they have a still more important function. Protons repulse each other being of the same charge, just like electrons in the shells of the atom. The electrons are needed to hold the protons together.

A simple calculation shows that the nucleus will require much more electronic glue than we have in our method of construction. There are still other, more convincing, objections to the presence of electrons in nuclei. We shall speak of them later on.

At this point theoreticians had serious doubts about nuclei consisting of protons and electrons. Then the neutron made its appearance. In that same 1932, Werner Heisenberg and the Soviet physicists D. Ivanenko and I. Tamm advanced a strong, mathematically supported hypothesis according to which nuclei are made up exclusively of protons and neutrons. The first step was taken.

The Second Step

In the construction of atomic nuclei, nature was just as economical as in the building of electronic shells. The only difference was that in

the nucleus it had two building stones—the proton and the neutron.

Each time a new proton was added, nature saw to it that the nucleus did not fly to pieces as the mutually repulsive forces of the protons built up. In the light elements (approximately up to calcium, No. 20), the number of protons and neutrons in the nucleus was about the same. After that, the number of neutrons grew faster than the protons, and this continued—the farther away, the greater the difference. In the uranium nucleus, with mass number 238 and 92 protons, we find 146 neutrons.

Seeing that the nuclear structure would stand, nature began to diversify its architecture—a few neutrons added here, a few taken away there. The result was isotopes—variations of a single element. The nucleus of tin, for instance, has ten stable isotopes.

It will readily be seen that the Heisenberg-Ivanenko-Tamm hypothesis is in excellent agreement with the data on nuclear masses and charges. According to this theory, the hydrogen nucleus consists of a single proton, the helium nucleus of mass number 4 (helium-4) consists of 2 protons and 2 neutrons, the lithium-7 nucleus has 3 protons and 4 neutrons, the boron-11 nucleus has 5 protons and 6 neutrons, the nitrogen-14 nucleus is composed of 7 protons and 7 neutrons, the oxygen-16 nucleus is made up of 8 protons and 8 neutrons, and so on and on.

And so on and on, right to the end of the Table this time.

What do we know about the neutron? This particle has a mass almost exactly equal to that of the proton and true to its name is electrically neutral—it has no electrical charge.

By what right does it occupy the place of the electron in the nucleus? The electron at least could hold the protons together. How can an uncharged neutron do this?

At this point we find out that the electrical forces of attraction are not enough to account for the stability of nuclei. Nuclei are real tough nuts. Not a single attempt to disrupt the nucleus by chemical means, by enormous pressures or temperatures or by fantastic electric fields has succeeded, though all such weapons have operated successfully against the electronic structure outside the nucleus.

Hence, physicists conclude, there is a definite reason for neutrons being in the nucleus. The neutron it is, therefore, that plays the role of cement in holding together the protons of the nucleus. But by what force, we ask. It can't be electrical, for the neutron is neutral.

Theoreticians got to work on this problem and two years after the discovery of the neutron, I. Tamm and the Japanese physicist Yukawa put forward a brilliant idea that there are very strong specific nuclear forces, exchange forces of attraction, of very short range operating between protons and neutrons.

Exchange forces? That's a familiar term. Those are the forces that hold two hydrogen atoms together or the atoms of nitrogen, oxygen and many others in rather stable molecules. In these molecules, the atoms are continually exchanging their electrons, and this holds the atoms together.

But what kind of exchange is there in the atomic nucleus? The proton and the neutron are two different particles. The nucleus hasn't got any electrons. What do protons and neutrons exchange? A calculation made by I. Tamm showed

that electron exchange yields too small a cohesive force for nuclear particles.

There are two ways open to us: either retreat and give up the exchange ideas as erroneous or strike out audaciously and state that despite the outward dissimilarity of the proton and neutron, these particles are actually not very different and have much in common, that they can convert into one another: the proton into the neutron and the neutron into the proton.

This idea is bold indeed. In 1934, the year this hypothesis was put forward, no interconversion of the elementary constituents of matter had yet been observed. True, two years before, the transformation of an electron and positron into gamma-ray photons had been established. But this phenomenon was of an utterly different nature.

Reasoning further, physicists figured that if two particles can convert into one another they should exchange something in the process. The proton acquires this 'something' and turns into a neutron; and when a neutron loses it, a proton appears. Then again, there could be a different kind of exchange in which the neutron acquires something and the proton does the losing.

Starting from the fact that nuclei are extremely stable structures and also that the exchange forces between protons and neutrons would have to operate over the extremely small distances between the particles, Yukawa blocked out the portrait of this material particle, this 'something'. It could have either a positive or a negative charge equal to the magnitude of the proton charge (or electron charge) and a mass approximately 200 to 300 times greater than the electron mass.

The proton and the neutron are roughly 1,800 times more massive than the electron. So the mysterious particle would have a mass somewhere in between the two. Whence the name: meson from the Greek meaning 'medium'.

Then we get the following picture of nuclear exchange. A proton emits a positive meson, loses its positive electric charge and converts into a neutron. A neutron picks up a meson and turns into a proton. But a neutron may emit a negative meson and become a proton in a different way. And this meson, when captured by the proton will convert it into a neutron in still another way.

The Search for the Mysterious Meson

But where are these mesons? Experiments with radioactive nuclei were repeated. The answer was a categorical NO! Even if mesons did exist in nuclei, they never leave them. As if mesons preferred to carry on their modest yet important work and never show up.

Then physicists turned to that great source of information about nuclear particles, the cosmic rays. Within the year the meson was discovered. In agreement with Yukawa's calculations, the meson had a mass of roughly 200 electron masses.

The theoreticians could celebrate. This amazingly bold concept of protons and neutrons being related particles and the discovery of the meson at the pencil point. One of the most remarkable attainments in physics ever!

But the elation was short-lived. The mesons refused to enter into any contact with atomic nuclei, were extremely indifferent to neutrons, and only bowed to protons within the ordinary

framework of electrical interaction. Physicists were stumped: Could this be the particle that was to go between proton and neutron and interact most energetically with them? Obviously, they reasoned, it couldn't be—surely not this quirk of nature. The search must go on.

This time nature played hide and seek with scientists for a real long time. Outstanding discoveries in nuclear structure were made, the secret of nuclear energy release was uncovered, the first atomic reactors and bombs were constructed, and still the elusive particle escaped detection. Only in 1947 was the noted cosmic-ray researcher Powell able to catch it.

This particle was again a meson, but a different one, not 207 electron masses but 273. There was no mistake this time. The new meson (called a pi-meson to distinguish it from the indifferent mu-meson) interacted strongly with nuclear particles. When it had considerable energy in flight, it could even break up nuclei that it encountered.

To summarize, then, the supposition of quantum mechanics that nuclear forces are due to a meson exchange between protons and neutrons was brilliantly corroborated. Incidentally, physicists were so sure of themselves in this question that they had continued pushing their way through the very thick of the nuclear forest without the slightest evidence of the needed meson even existing.

The Strongest Forces of All

Physicists immediately got down to a study of the newly discovered nuclear forces. The first thing they noticed was the extremely short

range of action. We have already mentioned that. The exchange forces in molecules begin to operate at interatomic distances of the order of the dimensions of the atoms—hundred millionths of a centimetre. Nuclear exchange forces have a range tens of thousands of times shorter. They begin to operate only at distances close to the dimensions of the nuclear particles themselves. And so, quite reasonably, they can exist only inside the nucleus and never display action outside.

Nuclear forces are the strongest yet discovered. Not only do they completely suppress the mutual antipathy of the protons, which is very great at such small distances, but even hold them tight in a stable structure.

Physicists describe the nuclear strength or stability in the same way they do for all bodies, molecules, atoms, nuclei—by the binding energy, which is the energy that must be imparted to an assembly of particles in order to break it up into its constituents.

Naturally, the more particles there are in a system, the greater this energy must be. To describe stability, we usually take the binding energy per particle. This energy is measured in special units called electron-volts. One electron-volt is the energy acquired by an electron when passing through a potential difference of one volt in an electric field. In our world of big things, this unit is very small, but for the atomic world it is quite appreciable.

The bonds between molecules of many substances break up even at room temperature so that these substances exist as gases under ordinary conditions. The binding energy between such molecules is of the order of hundredths of an electron-volt per molecule.

To break down these molecules into individual atoms, a much bigger energy is needed, roughly ten electron-volts per atom. This corresponds to impressive temperatures ranging up to thousands and tens of thousands of degrees.

To decompose atoms into their constituent electrons and bare core (nucleus) is still more difficult. We know that atomic electrons have different energies corresponding to their coupling with the nuclei. This energy range is from tens to thousands of electron-volts.

Nuclear particles have binding energies in the millions of electron-volts! Now it is clear why nuclei are unaffected by even the very strongest of nonnuclear forces. Even if two nuclei collide with speeds of thermal motion at thousand-degree temperatures, the effect will be hardly more than that of a rubber ball bouncing against a wall of granite.

Studying the work of the nuclear architect, physicists determined the stability of the various nuclei and plotted their findings as a function of the mass numbers of the nuclei. Take a look at the graph. The first thing we note is the tiny ups and downs, something like a mountain range. The similarity is strengthened by the fact that at first glance the peaks appear to be quite at random.

But before going on let us take a look at the lower curve. This is a curve of the abundances of the chemical elements in nature. To construct it, physicists had to consult geologists, astronomers, and even biologists. Obviously, the abundance of an element corresponds to the occurrence, in nature, of its atomic nuclei. By nature we mean, of course, not only the earth but the universe at large, the visible universe—as far

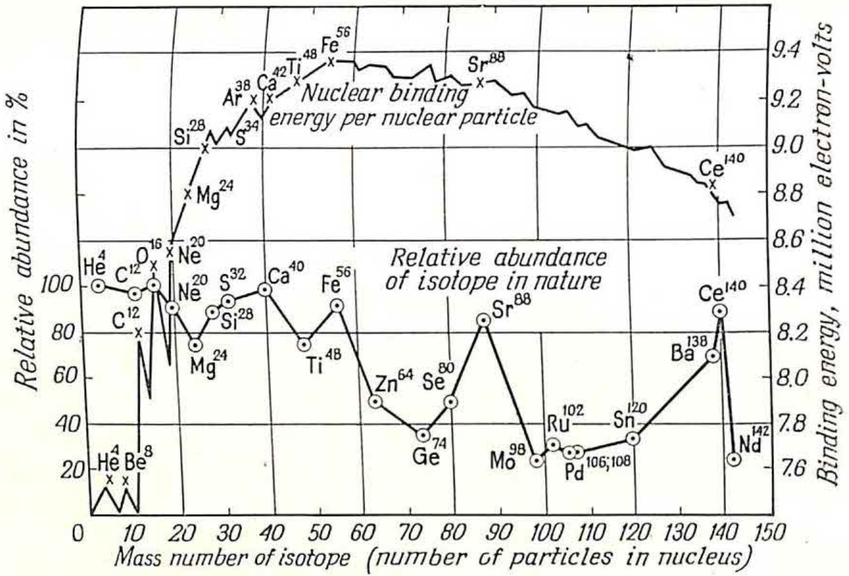
Nuclear binding energy per nuclear particle
Relative abundance of isotope in nature
Relative abundance in %
Binding energy, million electron-volts
Mass number of isotope (number of particles in nucleus)
He⁴ C¹² O¹⁶ Ne²⁰ S³² Si²⁸ Ca⁴⁰ Fe⁵⁶ Mg²⁴ Ti⁴⁸ Zn⁶⁴ Se⁸⁰ Ge⁷⁴ Sr⁸⁸ Mo⁹⁸ Ru¹⁰² Pd¹⁰⁶;¹⁰⁸ Sn¹²⁰ Ba¹³⁸ Ce¹⁴⁰ Nd¹⁴²
Be⁸ Ar³⁸ Ca⁴² S³⁴
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
20 40 60 80 100
7.6 7.8 8.0 8.2 8.4 8.6 8.8 9.0 9.2 9.4

Fig. 21.

as the spectroscope of the astronomer will reach.

Let us compare the two curves (Fig. 21). What have they in common? First, in the left-hand corner we notice that the highest peaks of the upper curve correspond to nuclei of helium-4, carbon-12, oxygen-16, and a number of others. All these numbers are multiples of four, as if these nuclei consisted not of protons and neutrons separately, but of alpha particles straight off. The corresponding portions of the lower curve indicate the highest relative abundances of these elements in nature—close to 100 per cent.

Continuing our trip along the mountain range, we see that the most noticeable breaks in the upper curve correspond to peaks in the lower curve. The more stable the nuclei, the greater, generally speaking, are its abundances in nature.

This would lead us to conclude that in the world of atomic nuclei nature has set up its own law of natural selection. In the struggle for existence, only the strongest survive. The most abundant are those whose neutron and proton numbers are 2, 8, 20, etc. We shall discuss the reasons for this later on when we talk about nuclear shells.

Here, we can point out that it is not exactly correct to say that nuclei consist of alpha particles. But one thing is definite: groups of two protons and two neutrons are indeed extremely stable even in the world of atomic nuclei. Physicists say that the nuclear forces operating between this number of particles become saturated. We find it impossible to try to add an extra proton or neutron to such a group. The helium nucleus, for example, refuses to accept anyone else into the family. Sure enough, this nucleus is the

most inhospitable one of all: there aren't even any nuclei with mass number 5 (two protons and three neutrons or three protons and two neutrons).

By refusing guests, the helium family strengthens itself. If we exclude the hydrogen nucleus (which consists of only one proton and therefore has no nuclear forces operating in it at all), the helium nucleus is the most stable nucleus in nature.

Saturation is a new property peculiar only to nuclear forces. Just as new and unusual is their property of charge independence. Nuclear forces just don't care about charge, they function just as well between a proton and a neutron as between a pair of protons or a pair of neutrons. Why this is so physicists don't fully understand to this day.

Once Again about the Stability of Nuclei

The exchange forces that form these strong nuclear structures are forces of attraction which bind the protons and neutrons together. To what degree can they pull together? There have to be limits, otherwise the particles would all merge into one.

Nature, naturally, does not allow this to happen; and to counter the powerful forces of nuclear attraction at extremely close encounters of nuclear particles there are no less powerful forces of repulsion that do not permit the particles to penetrate into one another.

This is the so-called lower limit to the range of action of nuclear forces. We have already spoken of the upper limit, which is obviously the greatest distance to which nuclear particles may

recede one from the other and continue to experience the constraining action of the nuclear forces. It is of the order of the dimensions of the nuclear particles themselves.

This is an interesting fact, for it can explain the general trend of the binding-energy curve: the fact that it falls with increase in mass number of the nuclei. Indeed, in a light nucleus that has few protons and neutrons, each particle may be linked to all the others by nuclear forces.

Now what about saturation, which indicates that nuclear forces prefer binding only tetrads (fours) of particles? The answer is simple. Nuclear particles are indistinguishable, and so there is no way to separate out such 'fours'. Try, in a crystal of sodium and chlorine ions, to isolate pairs that correspond to 'former' molecules. The same ions of sodium and chlorine in the crystal lattice of sodium chloride can enter into different 'former' molecules of NaCl, as we have already mentioned.

The more particles a nucleus has, the greater its size, naturally. Now each particle will be connected by nuclear forces only with its immediate neighbours. In place of the 'general' bond we have a chain of bonds, as it were. Such nuclei begin to lose their stability, all the more so since there is a general increase in the repulsive forces of the protons, which act in opposition to the nuclear forces, as the number of protons increases.

The largest and heaviest nuclei at the end of the Periodic Table of elements are rather unstable. Nature makes them become more stable of their own accord. This can occur only if the nucleus gets rid of any extra nuclear particles, just like a ship jettisons ballast to maintain buoyancy.

The extra particles which the nuclei eject are radioactive radiations.

Incidentally, you probably know that there are also a great number of radioactive nuclei both at the beginning and in the middle of the Periodic Table. However, most of them are not the products of nature but of humans. Bombarding originally stable nuclei with nuclear particles (mostly neutrons), physicists upset their equilibrium by overloading them with particles.

These nuclei return to their stable state, but not by the same route that they got there. What is more, the final state is usually different from the original state. A nucleus is upset by an extra neutron and it responds by ejecting electrons and gamma photons until it gets transformed into an entirely different nucleus.

Underlying this phenomenon, called artificial radioactivity, is the tendency of all nuclei towards stability, at all costs. Unstable things cannot exist for a long time. Recall the graph of the abundance of nuclei in nature. It clearly states that the more stable the nucleus, the longer it exists, and, hence, the more abundant is the element.

Tunnels in Nuclei

Very complex laws govern the stability of nuclei. They have been under study by scientists for over thirty years and still are not yet completely understood. However, some of these laws are giving up their secrets.

The first was alpha radioactivity, or the alpha decay of nuclei, which was discovered even before the neutron was, though science knew nothing of the underlying cause of the stability of alpha particles.

So we have two problems: Why do alpha particles fly out of nuclei, and why don't protons and neutrons fly out separately?

Let us start with the more difficult second question. Examining the curve of binding energy, we found that nuclei consisting of tetrads, pairs of protons and neutrons (for example, helium-4, carbon-12, oxygen-16), were more stable than their neighbours. Now we find that heavy radioactive nuclei decay precisely by means of these tetrad particles. How do we account for this ambivalent behaviour of alpha particles?

Our difficulties increase still more when we recall that nuclear forces in a tetrad reach saturation and it is impossible to add a fifth particle to the four. How, then, do nuclei heavier than the helium nucleus exist at all?

To answer these questions, let us look more closely at the existence of alpha particles, at the exchange of mesons between them. We know that one of the possible types of exchange consists in a neutron ejecting a negatively charged pi-meson and converting into a proton in the act, while the latter absorbs this meson and in a minute fraction of time turns into a neutron.

Thus, on an average, a tetrad all the time has two protons and two neutrons. But imagine for an instant that a meson ejected by a neutron in some tetrad is captured by a proton of an adjacent tetrad. Then there will be two 'crimes' committed at once: the first tetrad will have three protons and one neutron, and the neighbouring one will have three neutrons and one proton. Why 'crime'? Well, because, says the Pauli principle, protons and neutrons have the same spin as an electron and so have to abide by all the restrictions imposed on electrons. The Pauli

principle forbids more than one particle having a given sense of spin in a given state.

The alpha particle is extremely stable because the two protons and two neutrons in it each occupy a single energy level—the lowest possible. The two protons are on one level, and the two neutrons are on the same level. This is possible due to the fact that at each instant of time a proton and neutron in the nucleus appear in different guises, that is, are actually different particles. Now if a tetrad has three protons, then one of them will simply have to violate the stringent Pauli exclusion principle or will have to occupy a state of higher energy, which is to say a lower binding energy.

Nuclear particles do not wish to commit 'crimes'; neither do they like unstable states. What they do is immediately release the meson: we again find two ordinary tetrads. But this instantaneous exchange between the tetrads establishes a mutual bond between them. The tetrads become less isolated from each other.

The farther we go away from the light nuclei, the weaker are these effects of tetrads on stability. Yet the heavy nuclei again exhibit a definite influence of tetrads. Particles on the periphery of such nuclei, as we have already pointed out, can interact only with their immediate neighbours because the nucleus has become so large. Apparently, near the surface of nuclei we find particles forming into tetrads again since this is the most stable configuration.

This is probably the reason why heavy nuclei eject only tetrads (alpha particles) and not protons or neutrons. But how do they get out of the nucleus at all? The nucleus is a connected assembly of particles or, as called by its other

name, a potential well that is separated from the free existence of particles by a high barrier. We know the depth of the well (or the height of the barrier). It is equal to the binding energy.

We shall now see how the nuclear barrier differs from those we have already dealt with: no effort is needed to jump over it. The nuclear barrier is not a step with no back wall to it, but a 'fence', as it were. A fence not wide at all, but very high. To put it crudely, the width of the barrier is determined by the range of action of the nuclear forces, while the height indicates the magnitude of these forces.

Now quantum mechanics again takes over. The ejection of an alpha particle from a radioactive nucleus is a tunnel effect, say the quantum people, and this effect is in no way different from the tunnel release of electrons from a metal or the tunnel penetration of electrons into the conduction band in semiconductors and insulators. At all times, the wave properties are in operation; in one case, for electrons, in the other, for alpha particles.

Now we understand this 'double-deal' conduct of the tetrads. Actually, there is no double deal at all: everything is due to quantum probabilities. Theoretically, an alpha particle can even fly out of an oxygen nucleus, but the probability is negligible. In light nuclei the height of the barrier for ejection of alpha particles is very great (a large binding energy), while in heavy nuclei the barrier is low (a considerably smaller binding energy). Now the probability of the tunnel effect is very largely dependent on the height of the barrier, and falls off rapidly as it increases in height. Therein lies the whole secret.

On the other hand, the barrier height for ejection of alpha particles in heavy nuclei is much lower than that for the 'individual' release of protons and neutrons. That is why only tetrads fly out and not individual particles.

Does the Nucleus Consist of Shells?

Unlike the atom, the nucleus does not seem to have a central body surrounded by electron-like clouds. For some years after the discovery of the proton-neutron structure of the nucleus, physicists pictured the nucleus as more or less evenly smeared out nuclear matter filling this tiny volume of space in the form of a cloud of protons and neutrons.

However, the discovery of the saturation of nuclear forces and of the phenomenon of alpha disintegration seemed to indicate that the nuclear matter is not quite formless and that we perceive the outlines of small cells, so to speak, of alpha particles. As quantum mechanics and experimentation forged deeper into the nuclear forest, it became clearer that there are whole groups of trees, that it has shape and is not formless as when viewed 'from a distance'.

We already know that the particle tetrad occupies the lowest energy position in the nucleus and that it is the most stable of all the nuclear blocks. To this position there corresponds a single general level of energy at which we find two protons and two neutrons with spins in opposite directions.

In the given nucleus, the second tetrad of particles occupies a different energy level, the third, a third level, etc. As the number of particle

tetrads increases, higher and higher energy levels in the nucleus are filled, very much like the electrons in atoms.

But not all nuclei consist of tetrads! True enough. And this means that in nuclei with numbers of particles that are not multiples of four, the corresponding energy levels will not be fully occupied.

The nucleus is beginning to look very much like the outer structure of the atom, where we found filled and closed and stable electron shells (recall the inert gases). Here we have filled and extremely stable nuclear 'shells' made up of tetrads and larger numbers of nuclear particles.

Of course, an outward similarity in itself is not enough. We would like to have more tangible proof of the existence of shells in the nucleus. Let us take a look at our curves of stability and abundance of nuclei. Take a few of the very highest peaks and calculate the numbers of protons and neutrons in the nuclei that correspond to each.

The first is helium-4; its nucleus is an alpha particle and consists of 2 protons and 2 neutrons. Then comes oxygen-16 with 8 protons and 8 neutrons. This is followed by calcium-40 with 20 protons and 20 neutrons, and so on. Finally, at the right-hand end of the curve is the last high peak that belongs to lead-208; here the nucleus has 82 protons and 126 neutrons. (To these we must add the tin nucleus with 50 protons, which is so stable that nature devised ten stable isotopes, whereas other proton numbers have only 2 to 5 stable isotopes.)

So we now have the most stable nuclei with proton-neutron numbers 2, 8, 20, 50, 82, and 126.

Note that these nuclei are sort of counterparts of the atoms of the inert elements with 2, 10, 18, 36, 54, and 86 electrons. Both—each in its own world—are record-holders of stability.

These proton and neutron numbers were named 'magic numbers'. And so it should be, for there is something magic in the fact that the nuclei and electronic shells of atoms—two worlds that live by entirely different laws—should exhibit this common structural feature.

True, a comparison of the magic numbers with the electron numbers in the most stable atoms shows up a definite difference. These numbers coincide only for helium, which holds all records of stability in both worlds. It is no accident that these numbers diverge. On the contrary, it would be rather too remarkable if they coincided—so different are the living conditions in the nucleus and in the outer electronic cloud.

Still, there is something like a system of shells in the nucleus. There is also experimental corroboration. Let us take a look at the potassium atom (No. 19). It is univalent, which means that it has one electron outside the filled and closed shell of the inert argon atom. The total spin of the electronic structure of the potassium atom is equal to the spin of this valence electron. Which is natural enough, since the spins of all the other electrons are in pairs and in opposite directions so that they cancel and the sum is zero.

Now compare that with the nucleus of the oxygen-17 isotope, which has one neutron over and above four tetrads of particles. We should then expect that the spin of the nucleus of oxygen should be equal to the spin of this extra neutron. That is exactly the case.

This is not the only coincidence. The experimentally measured spins of nuclei are in excellent agreement with those predicted on the basis of the model of nuclear shells.

Where do Gamma Rays Come from?

Much more comes to light in the way of common features in electron shells and nuclear shells when we examine the origin of the third type of radioactive radiation—gamma rays. Physicists studying gamma rays were able to establish important facts about the lives of nuclear families.

The first fact to draw attention was the spectra of nuclear gamma rays; they were found to consist of separate lines. We already know what this means: that nuclear particles can have only very strictly definite energies, which also means that they have to exist in specific states. The transition of particles between such states would then give rise to gamma rays.

What are these nuclear energy levels and how do they fill up with nuclear particles? Here the map is mostly made up of blank spaces. The fact that a nucleus has definite energy levels should not cause any surprise. These levels are predicted by the Schrödinger equation for all connected assemblies of particles, which naturally include nuclear systems as well.

In the case of an atom, the formula that describes the interaction of particles is well-known, it is Coulomb's law for the mutual repulsion of electrons and their attraction to the nucleus. We put this law into the Schrödinger equation. But the law of nuclear forces is still unknown.

Physicists then have to solve the reverse problem: observe the spectra of gamma rays and calculate from them the energy levels in nuclei, their filling sequence. At one time, you remember, physicists busied themselves with just such a problem when combining the levels of energy in atoms. Scientists invoked information about the brightnesses of individual lines of gamma rays and their characteristics and attempted to derive a law that would govern the interaction of particles in nuclei.

It turned out a very tough nut to crack. And still isn't fully solved. Obviously, it won't be until we know something about the nature of nuclear particles. Some of the techniques now being used to approach this problem will be discussed in the next chapter.

Still and all, this concept of energy levels in the nucleus and of shells made up of proton and neutron 'clouds of probability' has been very fruitful. It has enabled us to explain the origin of gamma rays and the many interesting peculiarities they exhibit.

First of all, it is clear that to emit a gamma photon the nucleus has to pass from a stable state with least possible energy to a state with more energy, which by analogy with the atom is called an excited state. The gamma photon is emitted when the nucleus returns to its original state or to some other stable state.

Nuclear forces are millions of times stronger than electrical forces. For this reason, the distances between energy levels in the nucleus are usually much greater than the energy distances in the electronic structure. It is natural to expect that the gamma photons too have to be just as many times as energetic as the photons of light,

which means they will have a correspondingly smaller wavelength. That is exactly what we observe. Gamma rays have the shortest wavelength of all known radiations.

Now it is clear why gamma rays invariably participate in nearly all radioactive transformations of nuclei, for these transformations are nothing other than a transition of the nuclei into more stable states. At times a single readjustment of the nuclear house with a few extra particles thrown out is not enough for complete stability. The new nucleus, though more stable than the original one, is still in an excited state. Then the final stage in the reshuffle is an emission of a gamma photon; the nucleus then ceases to be radioactive.

The nucleus can also give up its surplus energy in a way that the electron shells of the atom have no idea of. Instead of shooting out a gamma photon, the nucleus gives up its excitation energy on the sly directly to the electron cloud. But this energy is so great that the nuclear 'gift' is more like an earthquake for the atomic building. True, the building continues to stand, but some of the electrons are fired out with very considerable velocities. This phenomenon competes very successfully with the direct emission of gamma rays and is called internal conversion.

The Nucleus as a Liquid Drop?

Nuclear shells, magic nuclei ... very pretty indeed. But this appealing picture could account for very many experimental facts that did not fit into the framework of the shell model. This should not be surprising. First of all, if nuclear

shells really existed, they would have to be very different from their electronic counterparts. The very concept of a shell in a nucleus was really farfetched. The nucleus has no core that could be surrounded by nuclear particles. More, the closed groups in the nucleus consist of quite different numbers of particles than in the outer part of the atom. Finally, nuclear shells would have to be of two kinds, proton and neutron.

So what the term 'shell' actually means when transported from the outer atomic world into the inner nuclear world is simply a certain kind of secludedness, stability, saturation of definite groups of nuclear particles. What is more, this does not occur all the time or at all places.

There was some justification in speaking of shells as concerns only the light nuclei which consist of a few nuclear particles. But as the nuclei increase in size, the separate energy states lose their individuality and the nucleus becomes structurally more and more shapeless. There are so many nuclear particles and their clouds overlap so much that there are no longer any definite particle motions and they cease, as it were, to obey quantum laws.

As a result, the nucleus loses all features of similarity with the atom. The shell model has to be given up. What new model can we devise for the nucleus?

Shortly before the outbreak of World War II, for reasons which we shall mention later on, scientists suggested the liquid-drop model of the nucleus. The nucleus was pictured as an outwardly homogeneous mass without any ordered structures in it (like, say, alpha particles or shells). The separate nuclear particles—the

molecules of the nuclear liquid—were supposed to be in a state of constant random motion in the liquid drop.

As a result, the nuclear liquid acquired a certain fluidity. Like a liquid drop, the nucleus has boundaries, but these boundaries are mobile, fluid, and can change form due to various external and internal causes. And all this without rupturing the surface of the nucleus, which is kept intact due to a certain surface tension of the nuclear liquid on the boundary of the drop. This nuclear surface tension is a complete analogy to that of ordinary liquids: the nuclear particles are bonded by forces of attraction not countered by any other forces outside the liquid drop. The nuclear forces hold the nuclear liquid in this drop.

There the analogy stops. Let us compare the densities of the two liquids. Simple calculations show that the particles of a nucleus are packed in thousands of millions of times more tightly than are the molecules of an ordinary liquid. A nuclear droplet the size of a drop of water dripping from the tap would weigh a good ten million tons!

Stupendous! Yet we know that the properties of bodies are very greatly dependent on their densities. Change the density of a gas one thousand times and it becomes a crystal obeying utterly different laws. It should be clear, then, that we cannot speak of any kind of internal similarity between ordinary liquids and the nuclear liquid. There is too great a difference in their density—thousands of millions of times—and the forces acting between nuclear particles differ radically from those acting between molecules.

But let's take a look from the outside; here we find an analogy. Put a droplet of mercury on a piece of glass and tap it lightly. The droplet shivers, ripples of wavelets race across its surface. Hit the droplet harder and it will break up into several smaller ones.

This may call to mind one of the biggest discoveries of physics in recent times. In 1939, the scientific world was hit by a sensation, the ominous meaning of which in those pre-war days was fully comprehended only by physicists. The discovery of the fission, or break-up, of uranium nuclei.

Theoreticians of different countries hurried to find an explanation for this startling phenomenon of the world of atomic nuclei. Independently, Niels Bohr and the Soviet physicist Ya. Frenkel came up with a theory. They succeeded in accounting for the fission of the nuclei of uranium in their newly advanced liquid-drop model of the nucleus.

The Liquid-Drop Nucleus Splits

Bohr and Frenkel reasoned something like this. Here we have a nucleus in normal life, there is even some order in the motion of the nuclear particles. If the nuclear structure is stable, its inhabitants carry on an even, secluded life.

But then, all of a sudden, in comes an uninvited 'guest'—a particle from somewhere. It plunges in and ruffles everyone. In the tumble and jumble of greetings, the nuclear house becomes pandemonium.

It is very soon impossible to distinguish the new particle from the others. The energy that it brought in is immediately distributed among

all the nuclear particles, so now neither the new particle nor any other particle of the nucleus can leave it. A new nucleus is thus formed. N. Bohr called it a compound nucleus.

But this state doesn't continue for long. One of the particles finally gets a strong enough bump to knock it across the potential barrier at the boundary of the nucleus, and leaves it. If the emerging particle is different from the one that entered, the whole sequence of events is called a nuclear reaction. The name is justified in that the initial nucleus differs from the terminal nucleus. Just like in chemistry where the initial substances differ from those produced in the chemical reaction.

The tumble and jumble of particles in a compound nucleus is very reminiscent of the random thermal motion of molecules in a liquid drop. From time to time, separate molecules evaporate from the drop. Which is much like the 'evaporation' of particles from a nucleus heated up by the impact of an outside particle.

What actually takes place in the nucleus in this case, nobody knows exactly. But we can say that it behaves as if it were a hot liquid drop. Let's take a look at the surface of the drop. It is all the time in a state of agitation, trembling, other molecules taking the place of the one that escaped.

It has long since been observed that the amplitude of oscillations on a liquid surface is very strongly dependent on the surface tension of the liquid in the drop, increasing as the latter diminishes. As we have already said, the surface tension in a nuclear liquid drop is due to the nuclear forces of attraction. The larger and more massive the nucleus, the weaker are these forces

and the more feeble is their hold on the nuclear particles. And in heavy nuclei, even relatively weak jolts can build up dangerous oscillations on the surface.

A knock of this kind can be produced by a neutron colliding with the massive and rather unstable uranium nucleus (recall that due to their instability these nuclei are radioactive). At times, just the slightest jolt will break up a uranium-235 nucleus, say in a collision with a thermal neutron, which is a neutron with an energy hundreds of millions of times less than that typical of atomic nuclei.

How does an ordinary drop of water divide? High-speed cinematography gives the answer. In the right type of collision, the droplet begins to resonate and high waves appear on its surface. Then the droplet stretches out into an elongated shape and finally breaks at the waist.

More complicated cases of the split-up of drops have been observed when they divide into larger numbers of smaller droplets, usually of different sizes.

Bohr and Frenkel presumed that nuclear fission is due to a similar deformation of the nuclear surface when neutrons impinge on heavy unstable nuclei.

The Secrets of Nuclear Fission

But why is the fission of nuclei due to neutrons? And why do massive nuclei prefer to fall into large pieces and not evaporate out individual particles, as in the case of artificial radioactivity in nuclei of small and medium mass?

In answer to the first question, we can say that the 'fence' which separates the nucleus from the

outer world has, as we have already mentioned, two sides. But they are not symmetrical.

On the inner side, the nuclear 'fence' is more sloping for protons than for neutrons. Its height is due to the nuclear forces and for protons is brought down because of their mutual repulsion. As a result of this barrier, the particles under ordinary conditions do not leave the nucleus. It is relatively stable.

Now on the outside, the 'fence' is somewhat different. For protons the barrier remains. This reflects the fact that the protons of the nucleus jointly repulse all unwanted guests of their own kind. Now for neutrons there is no outside barrier because they are electrically neutral. On the contrary, there is a well into which they can fall—when they fall into a nucleus, they usually stay there.

Therefore, if a proton wants to get into a nucleus, especially into a heavy, multiproton nucleus, it has to have enormous energy ranging up to hundreds of millions of electron-volts. Now a neutron doesn't need any energy at all. That explains why neutrons of very low energy (even thermal neutrons with energies of hundredths of an electron-volt) can enter a nucleus.

Now we can answer the second question. One might think that the neutron entering a nucleus of uranium-235 overloads it to such an extent that the latter falls to pieces. However, the neutron is not the last drop. This nucleus could, without any danger to its stability, accommodate three more neutrons to form a nucleus of uranium-238.

So what have we? The new neutron neither overloads the nucleus nor adds appreciable energy, nor, finally, does it give any kind of a

'kick' to the drop. Then how come the uranium-235 fissions?

The situation is indeed complicated, and we again come up against those quanta. The point is that a nucleus of uranium-235 is fissionable by a neutron of only a very definite energy. The energy limits correspond to the distance between the energy levels related to the stable and close-lying excited states of the uranium-235 nucleus. That is why neutrons whose energies correspond to the energy difference of the two states just mentioned are most effective in exciting uranium nuclei.

In the uranium-235 nucleus the energy distance between excited and stable states is very small. Once in an excited state, this nucleus, it would seem, should act like the light nuclei and emit a gamma photon and some particle, and then return to the same or some other stable state. But that is not what happens.

And here is why. We have already mentioned the fact that heavy nuclei prefer to eject alpha particles (tetrads) instead of separate particles. This is due to the fact that the potential barrier for the emission of alpha particles is considerably lower than for the ejection of individual nuclear particles. And it turns out that the barrier for such large 'blocks' as nuclear fragments in the fission process is very low in the case of the uranium-235 nucleus.

Once in the excited state, this nucleus is able to wobble over the tiny fission barrier and break up into fragments.

A very similar situation is found in the case of molecules. The energy required to eject even one single electron from the molecule is rather substantial. But the energy needed to split the

molecule into separate atoms is much less. That is precisely the reason why, in chemical reactions, molecules do not break up into electrons but into atoms or into groups of atoms (radicals).

The fission of uranium-238 nuclei by neutrons is very much like that of uranium-235. But in this nucleus the excited state is separated from the stable initial state by a rather broad energy range of a good million electron-volts. And so very fast and energetic neutrons are needed to raise such nuclei to the excited level.

How Many Nuclei Can There Be?

You've probably guessed that the number is definitely limited. The heavier a nucleus, the less stable it is. But even a uranium nucleus exists thousands of millions of years on the average before spontaneously getting rid of its 'extra' alpha particles and reducing to a more stable state. It is not difficult to calculate that heavier nuclei than uranium can live for quite some time before ejecting an alpha particle.

There is another thing, however, that puts a limit on 'weight categories'. We have just seen that with respect to fission into large blocks, heavy nuclei put up around themselves very low barriers. But then—yes, you've already guessed it—then a nucleus will have a perceptible probability of passing under this barrier.

No neutrons or any kind of excitation will be needed, the nucleus will split up spontaneously and pass through its own barrier in a tunnel fashion. Is that the way it happens? In 1940, nature nodded YES. The spontaneous fission of heavy nuclei was discovered by the Soviet phys-

icists Flerov and Petrzhak. It was no conjecture of quantum mechanics but an established fact.

And the heavier the nucleus and the more particles there are, the greater the probability of such fission. This is very rare in uranium nuclei, the probability is practically zero. But for californium (No. 98), the mean lifetime of nuclei for spontaneous fission is just a few years, not thousands of millions of years.

And finally we have a nucleus where the barrier to fission simply vanishes. A nucleus of this kind should have no resistance to fission. Actually, it would never get formed, for it would straightway fall to pieces. The last number in our list of 'standardized projects' for building atoms is 120. This means that nuclei (and the atoms as well, naturally) cannot, under any circumstances, have more than 120 protons.

It is the number of protons that decisively determines the stability of nuclei to fission. In heavy nuclei the forces of repulsion between protons increase drastically, and the nuclear forces of attraction between distant peripheral particles fall off rapidly.

As a result, near the nuclear surface we find raging protons, while the neutrons stand aside in the shade. The repulsive forces tear the surface to pieces and the nucleus breaks up into big blocks.

The Nucleus as Shells and Liquid Drop Together!

We have just discussed two models of the atomic nucleus. One of them offers the shell structure, somewhat reminiscent of the atom. The other

suggests the liquid drop. Which one of these models is closer to the truth?

The most reasonable answer is that both are good, but each in its own particular sphere of application. The shell model does a better job when describing the quiescent nucleus that has not been excited by any external causes. The liquid-drop model handles the situation best when the nucleus is under stress, when everything is boiling and the particles are energetically colliding with each other, when they evaporate out and when things get so bad that the nucleus splits to pieces.

Why not combine the two models into one that would be equally good in describing both types of phenomena? Well, we've already seen in the Planck theory of quanta why this joining of theories is not a tailor's job.

A united model of the nucleus, called a generalized model, was advanced a decade ago by the son of Niels Bohr, the noted Danish physicist Oge Bohr. Of course, this theory inherited certain of the features of its progenitors, but still was quite different from them.

Underlying the generalized theory is the contention that the nucleus behaves in shell-like manner when the numbers of protons and neutrons in it are equal to the magic numbers or close to them. Otherwise, the nucleus behaves like a liquid drop. What is more, this conduct is particularly evident when the number of particles outside the filled and closed shells reaches about $^2/_3$ of the number in the succeeding filled shell.

It turns out that the particles outside the nuclear filled shells are responsible for all the vagaries of the nucleus, from the ejection of individual

particles to the disruption of the whole thing. Now the particles in the filled shells behave much more modestly, taking no direct part in these activities of the nucleus.

Again we feel compelled to go back to the electron shells of the outer structure. You recall that the electrons in the closed shells of the inert atoms were snobbishly detached. At the same time, the electrons in the unfilled shells were active striking up acquaintances with neighbouring atoms to form molecules, crystals and to participate in chemical reactions.

Yet in the generalized model it is considered that there is not very much direct interaction of nuclear particles and that the shell aspect is not the most significant. Besides particle interaction in pairs, there is probably also a collective-type interaction of particles, which would better be reflected in a liquid-drop model. These events are manifested in deformations of the nuclear surface, as a result of which the nucleus does not have a spherical distribution of proton charge, and in a number of other nuclear peculiarities.

The electric, magnetic and other properties of atomic nuclei predicted on the basis of the generalized model are in good agreement with experiment.

Enough about models and the way physicists use them to describe the properties of atomic nuclei. These are not the only ones, many more have been conjured up.

Is it good to have so many models or is it rather a disadvantage? Most likely it is a disadvantage, for despite the manysided nature of the nucleus, it has, in reality, only one face. The multiplicity of models each of which is not bad,

yet unsatisfactory in one way or another, indicates that though the nucleus is a unity, it is a very difficult one to grasp and comprehend.

It is like a dozen photographs taken under different lighting conditions and at different angles, but only of tiny snatches of the whole picture. Naturally, from these bits it is hard to form an image of the whole.

In the case of atomic nuclei, the principal difficulty lies in the fact that we do not yet know enough about the nuclear forces.

These forces don't bother about the charge of the particles, they are operative only over short distances, and are very strong. We may add that, like all exchange forces, they depend on the mutual directions of spin of the interacting particles.

We shall get to know the nuclear forces better when physicists are able to peep into the interior of the nuclear particles themselves and comprehend their structure. Physics is only just approaching this problem, which contains a whole new world of research, probably even broader than that concerned with the atomic nuclei as such.

Particles Fly out of the Nucleus that Were Never There!

We already know how alpha particles and gamma photons get out of the nucleus. How do beta particles, ordinary electrons, come to be ejected?

When physicists attacked that problem some thirty years ago they were full of optimism. Just recently quantum mechanics had found the explanation of alpha and gamma radioactivity

of nuclei, and it seemed that beta radioactivity wouldn't stand unresolved for long. But nature was in no hurry to give up its secrets. Even today, physics has not fully conquered it.

The impasse out of which quantum mechanics can't seem to find a way is all the more exasperating since beta radioactivity is probably the most common form of decay of atomic nuclei. Since 1934, when Irene Curie and Frederick Joliot discovered artificial radioactivity produced in the bombardment of nuclei by neutrons, and especially after the advent of nuclear reactors made possible mass-scale bombardment, new radioactive nuclei that had never been known on earth before came flowing into the hands of physicists.

During the past quarter of a century, over a thousand new radioactive isotopes have been artificially produced. And the majority of them emit beta, not alpha, particles.

The first and principal difficulty in accounting for beta disintegration was that electrons cannot exist in nuclei. Earlier, when we were discussing the proton-neutron model of the nucleus we suggested why this was so. Now we shall give the main reason why electrons should not be found in atomic nuclei.

The point is that the electron cannot fit into the nucleus! An electron could be regarded as being in the nucleus if we could somehow drive in the whole cloud of probability. But even for exceptionally high speeds of the electron when its energy is of the order of nuclear energies, the length of the de Broglie electron wave is still hundreds of times greater than the dimensions of the nucleus. And the size of the electron cloud, as we have already seen in the case of the hydrogen

atom, is of the same order as the wavelength of the electron.

There was no room for the electron in the nucleus also because its spin, combining with the spins of the nuclear particles, would have produced incorrect values of nuclear spin.

Once convinced of this, physicists categorically deprived the electron of a haven in the nucleus. But then how does it happen that electrons come out of the nucleus, when they were never there to begin with? The nucleus has very massive particles that give birth to this extremely light electron. Like a little bullet coming out of the muzzel of Big Bertha!

A real wonder, this nucleus. What is more, an electron flying out of a nucleus violates two basic laws of physics: that of the conservation of energy and of angular momentum.

The Electron Has an Accomplice

In physics there are laws so fundamental that the entire edifice of science depends on them. These laws hold for all worlds and all phenomena.

One is that motion can neither be created nor destroyed. One type of motion can generate another type, motion can change form, can even become imperceptible. But it never vanishes.

At the dawn of classical physics, science felt the need for some measure of motion. One felt it necessary not only to describe motion but also to measure and count it. Two new quantities were introduced into physics: energy and momentum.

And the proposition that motion is neither born nor dies found its reflection in the invari-

ability of total energy and momentum of bodies taking part in some common action. The recoil of a gun, the heating of a working engine, pile driving, and numberless other instances—all meticulously obey two great laws: the conservation of energy and momentum. For rotational motion, a no less fundamental law was the law of conservation of angular momentum. Even figure skaters make use of this law. When they bring their arms together, rotation speeds up.

We can well imagine the consternation of physicists when it was found that the beta particles can have any energy value from zero to a certain maximum. The nucleus, it will be recalled—and it was clear to all at that time—is a quantum system and has definite levels of energy.

In other words, any process in the nucleus (an example of which is the ejection of a beta particle) can proceed only in such fashion that the nucleus moves from one definite energy level to another one. Which of course means that the energy difference and, thus, the energy carried off by the beta particle had to be just as definite.

Yet the spectrum of electron energy in beta disintegration did not exhibit even the slightest suggestion of lines corresponding to definite energies. All this signified that either the nucleus, despite the evidence of all other processes, did not in the final analysis obey the quantum laws, or that beta decay of nuclei violated the law of conservation of energy!

And not only that law. The electron carries out of the nucleus its energy *and* its spin, which is intimately bound up with the very essence of the electron. Then we find that after the ejection of a beta particle the nuclear spin remains the same. But maybe the electron leaves its spin in

the nucleus after all. No, that is absolutely impossible. That would be the same as an electron without charge, a piano without keys, a scientist without his head!

The reactions to all this were different. Some scientists had so much faith in the quantum laws of nuclear life that they proposed sacrificing the law of conservation of energy. They tried to dismiss it as being only 'classical'.

Others saw that that would not do at all. The idea was soon given up, yet there was still no way out of this critical situation. Then Wolfgang Pauli stated: "The electron 'criminal' has an accomplice." What's he like?

In beta disintegration, the nucleus acquires an additional positive charge exactly equal in magnitude to the charge of the released electron. The nucleus becomes ionized, as it were. Which suggests that the accomplice is chargeless, electrically neutral.

The accomplice should have a spin equal to that of the electron, but in the opposite sense. Both spins cancel, yielding zero. Then the spin of the nucleus, when an electron and its accomplice are ejected, remains the same, as required.

Finally, the electron and its mate carry off an energy equal to the maximum energy that electrons are capable of in beta decay of the nucleus.

This maximum energy is quantized, that is, it is exactly equal to the difference between the two energy levels of the nucleus prior to and following beta decay. But this energy can be distributed between the electron and its accomplice in any way. The division process is not governed by quantum mechanics and no restrictions are imposed on it.

Thus, quantization of energy in nuclei is preserved and the laws of conservation of energy and spin are not violated. Quite an ingenious way out of the impasse was found by Pauli.

Yet there is one more snag. The electron 'thief' is caught immediately, while its accomplice is exasperatingly elusive. "Well, what did we tell you?" say the skeptics. And physicists try their last card: indirectly they calculate the one remaining feature of the accomplice, its mass. An exact calculation is impossible, but it may definitely be stated that it is negligibly small, at least a thousand times less than the electron mass.

The phenomenal partner was at last found, but it had no charge and the mass was practically zero; all it had was energy and spin. The absence of charge made it look like the neutron, discovered just shortly before. Only it was lighter by a million times. So they gave it the diminutive name 'neutrino', or little neutron.

These two particles have nothing in common. Neutrons actively interact with protons, collide with them and form close-knit atomic nuclei. The neutrino? A bodyless spirit. Calculations say that a neutrino can pass through the entire visible universe—millions of light-years—and never give a sign of its existence. It would appear never to interact with anything.

Running ahead a bit, we might add that the neutrino was finally and definitely established by indirect evidence just a few years ago. The situation in the theory of beta decay was essentially the same as in the theory of nuclear forces. The latter hung in the balance for ten years until proof was found in the form of pi-mesons. The theory of beta decay advanced by Pauli together

with the Italian physicist Fermi was unresolved for a quarter of a century!

Let us now return for a moment. We've still got to find out where the electrons come from that fly out of the nucleus in beta decay.

Electrons are Born in Nuclei

We have already got used to the fact that marvels occur at every step in the world of ultra-small things. In the next chapter we shall have to do with an absolutely universal event, the interconversion of particles. We see that for the microworld, this interconversion is just as natural and commonplace as the relative constancy and stability of things are in our big world.

We are already acquainted with one such conversion. This is the mutual transformation of protons into neutrons and of neutrons into protons that lies at the heart of nuclear forces. In this process, a proton that has emitted a positive pi-meson converts into a neutron, while a neutron converts into a proton upon capturing a meson. But, as we recall, the neutron may emit a negative pi-meson and convert into a proton.

Maybe it is this meson that comes out of the nucleus in beta disintegration. No, precise measurements of mass have shown that this does not occur. The nucleus ejects not a pi-meson but a particle two hundred and some times lighter, the electron. Under the conditions of beta disintegration mesons never leave the nuclei.

We shall have to go ahead a bit once again. A few years after the discovery of the neutron, physicists established that this corner stone of atomic nuclei was an unstable particle. A free

neutron outside the nucleus converts into a proton in an average of just about 12 minutes after its birth. It is in this transformation that an electron and a neutrino are emitted!

The solution to beta decay now seems close at hand. Aren't these the two particles that come out of the nucleus? They certainly are. But a neutron in the nucleus is no free neutron. A nuclear neutron should turn into a proton in quite a different way.

Still, it seems a shame to give up this trail that took so much effort and time to find in the maze of beta decay. Maybe the neutron in the nucleus can become free for just a moment or two.

No, not even for a moment, to say nothing of twelve minutes. But we recall that nuclei which emit beta particles are either themselves unstable (for instance, the massive nuclei of elements towards the end of the Periodic Table) or are put into an unstable state by neutron bombardment. Now the emission of beta particles is nothing other than an attempt of the nucleus to pass from an unstable state to a more stable state.

A leaning wall may be held up by outside supports. In the atomic nucleus everything is done from within, and much better too. We have had occasion to compare protons with the building stones of the nuclear edifice, and neutrons with cement that holds them together in a firm structure. But what do we do if the building itself is not so solidly constructed or if it experiences a strong blow from outside—for instance, the impact of a neutron?

Nature restores equilibrium by converting cement into stones if there is too much, and stones into cement, if they are in excess and threaten the nuclear house.

These transformations take place with the ejection from the nucleus of 'surpluses' or 'deficits' of charge. A proton brick changing into neutron cement gets rid of charge and ejects it in the form of a positron (the positively charged mirror image of the electron). When a neutron turns into a proton, it ejects an electron and thus increases the total charge of the nucleus.

How fast do these transformations take place? Not in 12 minutes. We have already said that the position of a neutron in the nucleus is radically different from the conditions under which its free cousin lives. Sometimes the conditions in the nucleus are such that it cannot stand the unstable state for even thousandths of a second.

Sometimes these conditions inhibit the decay of a neutron or proton. Then the nucleus lives a long time before beta decay starts up, a very long time, sometimes as long as hundreds and thousands of years on the average. Generally speaking, there is nothing very remarkable in that—the living conditions of the nuclear particles are just as diverse as the number of different standardized nuclear structures.

At present, quantum mechanics cannot predict accurately the mean lifetime of beta-radioactive nuclei. This is due not only to the very approximate knowledge of nuclear architecture (which, in the final analysis, amounts to a knowledge of nuclear forces). The point is that quantum mechanics is not yet able to account in some reasonable way for the very fact of disintegration of a free neutron.

Underlying this disintegration are some marvellous forces the discovery of which in recent years has revolutionized many concepts of physics. But we shall talk about them in the next chapter.

Let us come back to some very interesting features of beta decay. One of them is that nuclei do not always eject only electrons.

It sometimes happens that the mirror images of electrons fly out of the nucleus. They differ from electrons in only one way—in electric charge; they are positively charged. It is even more difficult to account for this type of beta decay (which, incidentally, is less frequent than the ordinary electron-ejection decay). A neutron cannot throw out positive electrons. A proton could do this and turn into a neutron. But, unlike a neutron, a proton is absolutely stable with regard to beta disintegration.

And again we come up against the question: How can particles that were never in the nucleus come out of it? The situation now seems to be even more difficult. We can understand where electrons come from—from the nuclear neutron. But where do the positive electrons—the positrons—come from?

The answer has been found, but we will have to put this discussion off till our next chapter. Just a little more patience. If it will help any, we can say that the final stage is going to be really exciting. A little patience is all that is needed.

To pacify the reader we'll tell a little story about how the nucleus eats electrons out of the atomic cloud. Physicists named this ferocious behaviour 'electron capture'.

But how is this possible? At the very beginning of the book, we said that the quantum laws of atomic life discovered by Bohr indirectly reflect the impossibility of atomic 'suicide'. For this purpose orbits were introduced so that electrons

would not lose energy by radiation and would not fall into the nucleus.

In light atoms where the nuclear charge is small and there are few electrons, the prohibitions of quantum mechanics are stringently adhered to: the electron 'cloud of probability' does not get into the region occupied by the nucleus. But in heavy nuclei, the very deepest-lying electrons (in shells closest to the nucleus) find themselves in quite different conditions.

On the outside they are repulsed by large numbers of electrons, from the inside they are just as strongly attracted by the heavy positive nucleus. The electrons can't stand that ambivalent action for long. Electron clouds begin to push into the forbidden zone. A slight probability appears of atomic electrons finding themselves in the nucleus. And if there is a probability, sooner or later in some atom nature will realize it. This is the capture of an electron by a nucleus.

Now that we've got an electron in the nucleus, what happens? The charge of the nucleus will diminish by one unit, as in the case of positron beta decay. And the spin? The spin of the nucleus will remain the same, even though it received an extra portion from the electron.

If that is the case, then only one conclusion is possible: the spin brought in by the electron is carried out of the nucleus by another particle—the old partner of our electron, the neutrino. The difference now is that it is not released in a team with the electron but appears when an electron disappears in the nucleus.

And so the only witness to the 'murder' in the atomic interior is a neutrino, that elusive incorporeal spirit. As we know, to interrogate this guy is exceptionally difficult, well nigh impossible.

Yet in just recent years that has been done. And here's how. Our 'witness' can collide with another nucleus and convert a proton into a positive electron and a neutron, which is the inverse process of what we are going to discuss in the next chapter. It's called inverse beta decay.

To try to experiment with single neutrinos is hopeless. The only way is to collect whole armies of them. Then maybe a few can be caught.

That is exactly what was done when nuclear reactors began producing powerful fluxes of neutrons. When absorbed in the walls of the reactor, they induce artificial radioactivity. No small contribution is made by excited nuclei too, the fragments of disintegrating nuclei.

This is beta radioactivity. A nuclear reactor generates enormous quantities of neutrinos every second; with the greatest ease they pass through the reactor shielding that holds in neutrons and gamma rays.

Near the reactor was a very large scintillation counter.

It was filled with a liquid (toluene) which contained an abundant supply of hydrogen nuclei and scintillated when gamma photons appeared. The positrons generated in the capture of neutrinos quickly combined with electrons in the atoms of the liquid, yielding energetic gamma photons where they merged (for more details about this exciting event, see the following chapter). That is when the counter produced its first scintillation.

To facilitate neutron capture, chemically pure cadmium, whose nuclei avidly absorb free neutrons, is added to the liquid. Here too, neutron capture is accompanied by the emission of gamma photons and produces scintillation.

Thus, two scintillations separated by an interval of a millionth fraction of a second should give some clue to the expected phenomenon.

And these double flashes (which are very infrequent—only a few during many hours of reactor operation) were actually recorded. There could be only one cause: the collision of a neutrino and a proton to generate a positron and a neutron. Thus, a quarter of a century after Pauli advanced his hypothesis one more particle of the microworld, born at the point of a pencil, was identified.

Subsequent investigations showed that the neutrino is indeed one of the most remarkable of all microparticles. But that is a later story.

This completes our journey with quantum mechanics into the nuclear world. There are still many tangles and snags and pitfalls; in fact, no end of them.

We are now going into a still darker world, that of the elementary particles of matter, a world which manifests most clearly the regularities and laws that have been reflected in the wave properties of particles of matter and the material properties of waves.

From Atomic Nuclei to Elementary Particles

The Discovery of a New World

What, would it seem, could be more solid and stable than an atomic nucleus? It is unaffected by high pressures, extreme temperatures, enormous electric and magnetic fields. The strongest buildings of nature are nuclear structures. That was what physicists thought.

The development of science has since modified that idea quite substantially. Most heavy nuclei have proved to be very unstable. Even among the light and medium nuclei there were quite a few feeble structures. Gradually, it emerged that as nature lays the bricks in nuclear structures, the slightest deviations in the proportions of protons and neutrons in the nucleus make for instability.

At the same time, in order to account for the observed emission from the nucleus (during disintegrations) of particles that had never been inside it, science had to presume that the neutron in the nucleus could convert into a proton, and vice versa. This lead on to the idea of a neutrino.

The stability itself of the nucleus was, it appeared, due to a new particle called the pi-meson. In the search for this particle, physicists discovered the mu-meson.

Gradually, it dawned on scientists that the world of building stones that make up atoms and their nuclei was not quite so invariable and stable as had been thought. In the depths of the atom and in the still greater profundities of the atomic nucleus, investigators encountered events that outmarvelled all the predictions of quantum mechanics.

But quantum mechanics coped with this new situation too. Its remarkable capacity for predictions flowered in the new world of elementary particles. Skeptics were thunderstruck as each new prediction was brilliantly corroborated by experiment. This was all the more remarkable because each new step in the ultramicroworld was a contradiction of common sense.

Common sense, indeed! Science would still be crawling along at a snail's pace if scientists were guided solely by everyday common sense.

The most extraordinary discoveries are usually made when common sense goes topsy-turvy. The true essence of many things lies not on the surface but deep down. The commonplace and the obvious are frequently deceptive. This word 'frequently' becomes 'always' when science delves into the fantastic world of the ultrasmall.

Let's go back to the year 1928. The new world is just beginning to unfold. We have learned of two particles, the proton and the electron. Quantum mechanics is only three years old. True, it has been very successfully solving one enigma after the other. We have at last properly grasped the hydrogen atom, the formation of hydrogen

molecules, the tunnel effect has just helped us to understand the emission of alpha particles by radioactive nuclei. We still know practically nothing about nuclear and other particles.

Then out comes a young English physicist, Paul Dirac (how young indeed they all are: Schrödinger 38, Heisenberg 28, and Dirac 25), and says that the successes of quantum mechanics may turn out to be short-lived, for this theory grew out of classical physics which described only relatively slow motions of bodies.

Yet, can we consider the motion of an electron in an atom slow even in the old Bohr theory, when the electron orbits the nucleus millions of millions of times every second? In light nuclei, the electron has velocities of the order of thousands of kilometres per second, in the heavier nuclei velocities rise to hundreds of thousands of kilometres per second.

Definitely not slow! Which means we've got to extend quantum mechanics to these fast motions of atomic particles. But how?

About twenty years earlier, a theory appeared which dealt precisely with the fast motions of ordinary bodies. It was called the special theory of relativity. The author was Albert Einstein.

Dirac concluded that the way to extend quantum mechanics to the fast motions of microparticles was by combining it with the special theory of relativity.

The Invisible Dividing Line

In this small book we cannot, of course, give a detailed description of the theory of relativity. It would require another whole book of its own,

so we shall take a look only at what is directly connected with our story.

First of all, let us figure out what is to be termed fast and slow motions. In ordinary life this is fairly clear: a snail's pace is slow and a jet aircraft is fast.

Subjective? Yes. But the measure of slowness and fastness was man's movements, the way he walks or runs.

But take a long look at a fast train in the distance—how slow it moves. Or a jet plane far off in the sky, again slow. Even an artificial satellite doesn't seem to move fast. Fast and slow are relative concepts, very much so, in fact.

Physicists were not satisfied with such notions. They needed some kind of constant measure of velocity not connected with human beings, so that it could be used to evaluate all other velocities of motion.

Maybe take the speed of the earth in its orbital progress about the sun? Not so bad, generally speaking. But since man has penetrated telescopically deep into space, it would be better to find a measure not connected with the earth or the sun or, in fact, with any specific astronomical body. Something applicable to anything in the universe, universal.

Nature graciously offered the velocity of propagation of electromagnetic waves in vacuum, the velocity of light photons in empty space. This speed is roughly 300,000 kilometres per second and is the greatest of all known velocities.

There is nothing faster, all motions relative to that of light are slower. Physicists use the term 'fast' for those motions which are close to the

velocity of light. This is a rather arbitrary division, actually only a convention, but there is profound meaning in it.

As velocities approach that of light, the properties of the bodies begin to change substantially and unexpectedly, especially objects consisting of large numbers of particles. Here, it is easy to account for such changes.

One obvious change is the increase in mass of a body as it approaches the velocity of light. The closer it gets to this velocity, the greater the increase in mass. Outwardly, this is seen in the fact that the body begins to resist the force that is increasing its speed. As a result, a greater and greater force has to be applied in order to build up the speed of the body.

But there is no force great enough to make it move with the velocity of light. The theory of relativity states that no material body can be made to move at that velocity. By material body we mean any body (or assembly of particles) that can be at rest. Photons, as we shall see later on, cannot be at rest, and so the theory of relativity does not apply to them.

In the language of mathematics, this idea is expressed by the famous equation

$$m(v)=\frac{m_0}{\sqrt{1-v^2/c^2}}$$

Here, $m(v)$ is the mass the body has when moving with a velocity of v; m_0 is the so-called rest mass which the body has when it is not in motion, and c is the velocity of light.

From this relationship it is clear that as v approaches c, the denominator diminishes, first slowly and then faster and faster. Accordingly, $m(v)$ increases, since m_0 is a constant quantity

independent of the velocity. Finally, when v equals c, the mass of the body $m(c)$ becomes infinitely great. In other words, the body should have an infinitely great mass.

It is obvious that only an infinitely great force could do such a thing. But nature knows no such infinite mass or infinite force. The universe as such is infinite, but there are no other infinities in it.

We have already said that this formula cannot be applied to photons. Rather, it doesn't yield anything. Photons cannot be at rest. We can say this differently: the rest mass of a photon is zero. Putting this value for m_0 into our relation, we find that for a photon velocity equal to c, the mass $m(c)$ would be 0/0. Mathematics says that this is indeterminate, which means it can have any value whatsoever.

That is exactly the case, as we shall see later on: the mass of a photon can be anything, large or small. But it exists only when $v=c$. All of this means that photons can move only with the velocity of light.

That's the velocity of light, for you! No material particle can have it and at the same time no photon can have any other velocity. And so the velocity of light is an unsurmountable barrier between material particles and photons.

Why don't we notice the mass increase predicted by relativity theory in ordinary life? Let us examine the escape velocity of a rocket moving at 11 kilometres per second. We calculate the increase in mass over the rest mass it has on earth. If it weighed 100 kilograms on earth, the 11 km/s velocity would increase its mass by 0.35 milligram!

But if we get the speed up to 250,000 km/s, its mass will increase more than twice over the rest mass. That is what happens to charged atomic particles accelerated to high velocities in special machines called particle accelerators. That is what designers have to keep in mind when constructing such devices.

A Bit More about the Theory of Relativity

Changes in velocity that bring bodies close to that of light have other things in store for us. The mass changes and the very course of time itself is altered. Physicists call it the proper time of the body. Our bodies have their own 'clocks', as it were. They tick in step with the rhythm of the vital body processes.

On the other hand, we get up, go to work, and go to bed in accordance with the 'general' time, the time of ordinary clocks, which are geared to the alternation of day and night, to the rotation of the earth on its axis.

"How fast time is flying", or "How time drags on"—that is our own time we are talking about, our subjective time geared to our bodily functions. Yet there is an objective side to this too. The faster the rhythm, the faster the time.

There is a very definite analogy of this in relativity theory. Relativity theory states that the faster a body is moving, the slower its proper time flows so that the body views 'general' time as flowing faster.

This 'clock paradox' is familiar talk today because of interest in long-distance spaceflights. In science-fiction stories, astronauts moving in photon rockets at velocities close to that of

light return to earth after a cosmic voyage of, say, 10 years, and find that their friends have aged tremendously. "How the years flew by," they say. Which is true, because on the spaceship the proper time flowed more slowly than on the earth.

What we have described about the time may be expressed mathematically as follows:

$$t(v)=t_0\sqrt{1-v^2/c^2}$$

Here, $t(v)$ is the time proper of the astronaut's watch, t_0 is the time reckoned on an earth clock. The other quantities in the equation have their ordinary meaning. From this formula it follows that for photons moving with the velocity of light, time doesn't move at all! If we could put a clock on a photon, time would stand still—the clock wouldn't go.

Relative theory has other paradoxes, but we shan't deal with them here. We have one more equation that will play a very important role later on. This is the famous Einstein equation

$$E_0=m_0c^2$$

Here, E_0 is the energy of a stationary body with rest mass m_0. To distinguish it from the kinetic or potential energy, we call it the rest energy or the energy proper of the body.

It will be seen that it is independent of either the velocity or the position of the body. Classical physics knows only two types of energy. This new type has no place in classical physics. It is something very special that will be taken up a bit later. For the present let us return to relativity theory and how it was introduced into quantum mechanics.

So we have Dirac trying to combine the two greatest theories of the twentieth century. This new 'alloy' should strengthen the quantum theory in the face of an onslaught of new facts from the world of the ultrasmall.

The Schrödinger equation was a quantum mechanical passkey to all kinds of safes of nature. But certain facts it couldn't handle, so ways were sought to improve it.

It was soon found that to 'alloy' this equation with the theory of relativity was no easy job. The first thing that Dirac thought was that the modified equation would yield relativistically invariant solutions. (The future showed he was not exactly right. But who knows, if it hadn't been for this 'happy' error, Dirac might have passed by a remarkable discovery!)

Relativistically invariant—terrifying words these. Actually, a frightening sentence to all physical theories. A theory with this label can be thrown out, it is simply no good.

The gist of the matter is this. Have you ever tried playing ball on a boat? Try to imagine playing ball on an airplane. Is there any difference from the game on the ground? That's right, there isn't. True, with one proviso: the boat or plane must be in uniform motion at a constant velocity.

There is no way of distinguishing rest from uniform motion, no matter what the speed. Without the alternation of day and night we wouldn't be able to perceive the motion of the earth on its axis. Without the change of seasons we wouldn't know the earth was moving round the sun. Strictly speaking, the latter two exam-

ples are not exactly true, because rotation is always accelerated motion. But in our case the accelerations are so insignificant that we can regard both motions as uniform.

All the motions of bodies in a spaceship moving with a velocity close to that of light should not differ from those on the earth (if, of course, the gravitation is the same, that is, if it has been artificially produced in some way on the spaceship). And since the motions of bodies do not depend on the velocity of the reference system used to reckon their positions in space and time, whether it is the earth or a spaceship, the laws of motion of these bodies must also be independent of the system of reference.

In all reference systems, no matter with what velocity they are moving uniformly relative to one another, the equations of the laws of motion must be the same. In other words, these equations must be invariable relative to different velocities.

These words 'invariable relative to' are translated into the language of physics as 'relativistically invariant'. Their grim meaning is this: if an equation states that in a spaceship moving at a velocity close to that of light a ball describes a hyperbola, while on earth it describes a parabola, then the equation is faulty and has to be discarded.

That is what happened when attempts were made to modify the Schrödinger equation.

An Unexpected Discovery

In his search for a way out, Dirac proposed an unusual thing—he introduced into the Schrödinger equation four wave functions in place of one.

The resulting equation was quite unlike the original one. But the new equation yielded excellent relativistically invariant solutions.

There were four solutions, according to the number of wave functions in the equation. But how are we to comprehend four 'probabilities' for an electron in place of one?

The meaning of the first two solutions would probably have remained obscure for many years if electron spin had not been discovered three years before.

So the first two solutions of the Dirac equation correspond to the two possible senses of electron spin relative to the direction of motion of the electron. The spin was calculated from this solution and it proved to be in excellent agreement with experiment!

Now we'll have to talk a little more about spin. First of all, spin corresponds to some sort of motion of the electron when the velocity is close to that of light. Indeed, if for a moment we try to interpret spin as the result of an electronic 'rotation on its own axis' (we have already said that such a notion is completely wrong), it will turn out that the velocity of the electron in this 'rotation' is only the smallest fraction of a per cent less than the speed of light.

It stands to reason that the motion which we have in view when speaking of spin has nothing whatsoever to do with the ordinary motion of an electron in ordinary space. The spin of an electron is in no way dependent on ordinary motion. It exists irrespective of whether the electron is moving fast or slow or is at rest. The value of the spin is always the same.

The spin is just as intrinsic a property of particles as, say, their rest energy. If we change the

spin, we change the type of particle. We'll be returning to this again.

How is spin manifested? A little was said about this when we discussed atomic spectra. As far back as the end of last century, it was found that if a substance is introduced into a magnetic field, its spectral lines get split into various numbers of fainter lines. It was later established that a similar splitting is experienced by the spectral lines of the atoms of all elements.

An understanding of the nature of this phenomenon (called the Zeeman effect) and especially the reason for line splitting into different numbers of 'satellite' lines was obtained only in 1925 when two young physicists Uhlenbeck and Goudsmit introduced the notion of spin.

Subsequent reasoning went like this. The electron has spin, that is, in the final analysis, angular momentum. The origin of it does not interest us yet; the important thing is that it corresponds to some kind of motion of the electron. But electron motion is electric current—current due to a single particle. 'Real' current is produced by the motion of large numbers of electrons.

Current, as has been known for over a century, is capable of magnetic action. Put otherwise, an electron may be pictured as a minute constant magnet. If an elementary magnet of this kind is introduced into a magnetic field, it will orient itself in this field. In the simplest possible case we have two orientations: one with the magnetic field (absolutely stable), and the other counter to the field (absolutely unstable).

Now what is stability? When a magnet aligns itself with the field, its potential energy in the

field is a minimum. In the counter-field case, the energy is a maximum.

What quantitative difference is there between these energies? This can be easily calculated and converted to a difference of wavelengths of photons emitted in an atom by electrons with spins with and counter to a magnetic field.

Then it appears that all doubled spectral lines are split exactly the number of times yielded by the two opposite orientations of electron spin!

The next question is about the 'fat' lines that have split up into three, four and larger numbers of satellites. The two orientations of spin yield only a pair of satellites! And there couldn't be any more because the electronic magnets jump straight through to the most stable position.

At this point we recall that the electron participates in this new motion that produces spin and is also in orbit about the atomic nucleus. Actually, this orbital motion is also a quasi motion of sorts. The notion of a 'cloud of probability' does not permit us to think up a more pictorial image of electron motion in the atom.

Still, it is motion, a kind of unitary current, and the action it produces resembles that of a small magnet. Things are now fairly complicated: an electron in an atom is like a double magnet.

How does such a magnet behave in a magnetic field? Strangely enough. In place of two orientations we have three, four and even larger numbers. As the elementary magnet of the electron passes from a less stable orientation to a more stable orientation, it can come to a stop at a number of intermediate positions. The energies of these positions are integral fractions of the maximum

energy between the extreme positions of the magnet. Which means that these are very definite energies separated by quantum intervals of a specific magnitude. Physicists called this phenomenon of definite orientations of electron magnets in atoms in a magnetic field 'space quantization'.

Now the rest becomes comprehensible. A spectral line splits into just as many satellite lines as there are orientations that can be assumed by the electron magnet. Calculations of differences of satellite wavelengths likewise exhibit excellent agreement with experiment.

For the time being that is enough about spin, which came up so suddenly from Dirac's equation. The equation has two more solutions.

A Still More Unexpected Discovery

These two solutions are very much alike, just as the first two corresponded to opposite orientations of electron spin.

Here, too, we have two opposites: one of the orientations corresponds to positive total electron energy and the other to negative total electron energy. Nothing surprising, you say, we have already seen that the total energy can have either sign, depending on whether the electron is in free flight or is associated with other particles, as in an atom.

But the Dirac equation is written only for a free electron!

"Hhm!" So the Dirac electron is free and bound at the same time. Nonsense!

Dirac himself realized that this was nonsense. The simplest thing, of course, would be to dis-

card what you don't need, just like one does when he gets a plus-or-minus 20 square metres for the area of a room. The negative value runs counter to common sense. So we could reject the negative energy of a free electron as being physically meaningless.

However, Dirac did not hurry to do this. Like the Englishman that he was, he may have been full of common sense. But as a scientist he went to look for the origin of the nonsense. For it might be that even nonsense has some meaning.

Dirac finally came up with an exciting idea. It might be that the 'crazy' solution belongs not to an electron but to some other particle with charge opposite to that of the electron. The electron charge is negative, so this particle should have a positive charge. Both should be equal, however, in absolute value. Dirac thought that the proton might do, but it was soon found that the negative energy had to belong to a particle with mass exactly equal to that of the electron. The proton would definitely not do, for it was nearly two thousand times more massive than the electron. The only possibility was a mirror image of the electron.

However, this picture doesn't explain the negative total energy of such a positive particle. If the energy is negative, that means the particle is bound to something. The electron is absolutely free, all other particles, upon solution of the equation, are removed so far away that electrical interaction can be disregarded. The electron is alone in motion in a boundless and absolute void. Where then do we get this second, positive, particle, the mirror image of the electron?

At this point Dirac got the craziest notion of all. The void, the vacuum, which does not contain a single particle except the sole electron, is not empty at all! Quite the contrary, it is filled to overflowing with electrons! The positive mirror image of the electron is a hole in a filled emptiness!

Madness, complete madness, yet there is an audacity here that saves things.

What do we call space in which no instrument, no matter how sensitive, will ever be able to detect a single particle? Empty!

Now take it easy. Suppose it contains particles that cannot interact with the instrument. Then even if the space is loaded with particles, you will continue to call it empty space.

True enough, but how can particles be divested of their ability to interact? Doesn't that contradict their very essence?

Conclusions can wait a bit. Let us first try to probe the structure of a metal with a weak electric field. We detect current and we say that the metal is filled with free electrons. However, if we confined ourselves to this single experiment we would get a wrong conception of the metal. For there are still atoms there whose electrons cannot interact with, say, an ammeter. These electrons reside in atomic levels, in a 'well'. And they are not able to get out so as to interact with the measuring instrument because they haven't energy enough.

Of course you will say that with a different instrument and in a different experiment it should be possible to find atoms and even atomic nuclei in the metal, whereas a vacuum is not detectable by any kind of instrument. Hence, there is nothing in it and there can't be anything.

So says common sense. Dirac says differently. The vacuum is completely filled with electrons. The entire universe takes part in the formation of a unified vacuum of infinite extent. Infinite quantities of electrons in it fill infinitely great numbers of energy levels of the vacuum, forming a unified and interrelated assembly of particles. In accord with Pauli's principle, each level can accommodate two electrons with opposite spins, and no more.

The common 'universal well' in which the electrons are located is both capacious and deep. Its top energy level lies at the energy distance of m_0c^2 from the zero of total energy downwards. And so all the electrons in the vacuum must have negative energies.

No instruments can detect these vacuum electrons until they jump out of their well. Obviously, the first thing to do is impart to them an energy of m_0c^2. Yet that is not enough. We have already seen that every particle, whether at rest or in motion, has a proper energy m_0c^2.

In order to get out of the vacuum, the electron must not only overcome the barrier of height m_0c^2; it also has to acquire the rest energy m_0c^2 to which it is entitled. Whence we see that the total height of the barrier separating vacuum electrons from their interaction with an instrument is $2m_0c^2$.

That is quite a substantial energy. Suffice it to say that it is only within the past thirty years that physicists have been able to impart to electrons energies of this magnitude. When Dirac proposed his 'overloaded' vacuum, energies like this were still being dreamed about.

But why can't electrons interact with the instrument while in vacuum along the lines of

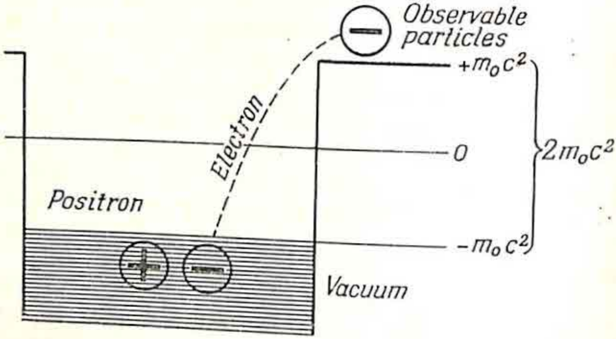

Fig. 22.

what happens in metals? Again the Pauli principle gives the answer.

Every interaction of bodies is a change of their energy. It is via this change that we detect the interaction. By interacting with an instrument, an electron in vacuum could change its energy and pass to some other level. But the trouble is that all the levels in the vacuum are filled to overflowing with electrons! There simply is no place.

That is why vacuum electrons cannot be detected. They exist in the vacuum, but they cannot interact with each other or with any instrument. These electrons can coexist with us for any length of time and we will never suspect anything, for they never make their whereabouts known in any way.

The Birth of a 'Hole'

Let us suppose that for some reason (what the actual cause is is immaterial at this point) an electron in the vacuum acquires enough energy

to jump out. Now that it is free the total energy of the electron is positive. What happens in the vacuum?

A hole is formed. The site in the vacuum where the electron had been becomes, as it were, ionized; it gets a positive charge equal in magnitude to the charge of the electron.

Now a hole is something we remember from our dealings with semiconductors. There, an electron jumped into the conduction band and left behind a hole in the filled valence band, in which it had negative energy. A remarkable analogy, which by the way, ends right there. In semiconductors, the hole is indeed an 'empty site' introduced for the simple convenience of describing different types of electron motion in the valence band and the conduction band.

The hole in a vacuum is something quite different. Here, it is in no way different from the electron. It is a real particle, just as real as the electron. Like the electron, the hole has a rest energy of m_0c^2, which is an energy equal to the depth of the topmost energy level in the vacuum well.

In other words, the electron and hole originate out of their vacuum 'nonexistence' only in pairs. The energy expended in the production of each particle is m_0c^2 (their masses are equal), or $2m_0c^2$ altogether, as we have already mentioned.

The electron can roam about the 'free world' and then return to the vacuum. To do this, it has to meet a hole and merge with the latter. Then it will be nonobservable again. The hole vanishes too.

But that's not all. Before returning to the vacuum, the electron has to give up the energy

consumed in ejecting it from the vacuum, or, to put it otherwise, the energy used to generate it and the hole, that same $2m_0c^2$.

In what form will the energy appear? As gamma photons, which will fly out of the site at which the electron and hole merged and will carry off this energy.

The last question is: Why is the energy taken up by gamma photons? The simple point here is that the energy given up by the electron-hole pair before it drops into nonexistence is big enough to correspond to hard gamma rays. No less than two (and rarely more) gamma photons are generated because the merging electron and hole have opposite spins.

This is all very natural: since the total momentum of the electron and hole in the vacuum is zero, the momenta cancel when they merge. So a gamma photon needs a partner with opposite momentum so that their total momentum will be zero. Such are the requirements of the conservation laws which we mentioned earlier.

If a third body (say, a nucleus) happens to be near the encounter of an electron and positron, it can take up some of the energy and momentum of the colliding particles. Then there will be one photon in place of two.

The Outlines of Emptiness

Physicists listened to Dirac and shook their heads. Even the most devoted adherents of quantum mechanics refused to take Dirac's theory as anything more than a good physical joke. Will power was needed to stand by this 'crazy' hypothesis.

The day was not far off, however, when the skeptics and scoffers had to retreat in disgrace. The day of a discovery that brought triumph to the Dirac theory.

In 1932, the Englishman Blackett and the Italian Occhialini exposed a photographic plate to cosmic rays and detected two tracks corresponding to an electron and to an unknown particle of the same mass but with positive charge. The tracks forked out from a single point in different directions. Since the photograph was made in a special chamber placed in a magnetic field, the different directions of the tracks definitely indicated opposite charges.

Thus the hole was recognized and given the name positron. It was the first in a series of microparticles now called antiparticles. We shall come back to them a bit later.

The Dirac theory would have an honoured place in physics even if it stopped with this single prediction of the positron. But it didn't. Dirac opened the eyes of physicists to utterly new aspects of the world of the ultrasmall.

First of all about the vacuum. According to Dirac, it is filled with electrons that do not interact with particles in the 'above-vacuum' world. When an electron leaves the vacuum, a positron is immediately generated. These particles are born and die only in pairs.

But then maybe we could say that the vacuum is filled with positrons and that electrons appear only when positrons leave the vacuum. In its original form, the Dirac theory considered both equally possible. However, we give preference to a vacuum filled with particles and not antiparticles. The reason is that electrons are everywhere about us, while positrons are indeed a rare

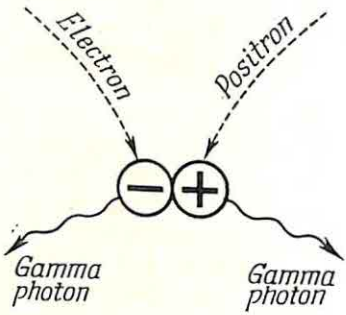

Fig. 23.

guest in our world. From this we ought to conclude that there are far fewer positrons in the world than there are electrons. But the Dirac theory states that one particle originates only with the other, its antiparticle. Which means that the number of electrons and positrons in the world should be the same.

Strange! Still stranger is the fact that our world exists and we exist too, for there is nothing to prevent all the electrons from colliding with positrons and falling into the vacuum, leaving behind a disembodied trace in the form of gamma photons.

However, an electron doesn't often meet a positron, in fact, rarely indeed. So there is no reason to get worried about the world becoming a vacuum. And so there are more electrons than positrons! But where do they go to?

One might think that nature did her best to keep the positrons and electrons as far apart as possible. This is a popular idea among science-fiction writers and certain scientists. They

Fig. 24.

maintain that somewhere in the universe are worlds made of antiparticles, so-called mirror worlds. In those worlds, the positron is boss and electrons are occasional guests.

The next question is: If the electron has its antiparticle, why shouldn't the proton have an antiparticle as well? But then we should have a vacuum of protons! And, generally, every particle should have its antiparticle and, hence, its own vacuum. Then the vacuum should be filled (completely filled!) with neutrons, neutrinos, and mesons. Some void! Rather more like a limitless repository (well) for all 'unborn and dead particles.

Quite impressive, but somewhat too unwieldy. In a little while, physicists gave up the Dirac vacuum and replaced it with more elegant conceptions, which we shall discuss later.

Particles can get out of the well only in pairs after acquiring sufficient energy. The first to emerge are, of course, the lightest particles, the

neutrinos and electrons. For a proton and antiproton, this energy should be at least two thousand times that for an electron-positron pair. The more massive and sluggish the particle, the more difficult it is to get out of the vacuum.

Complete Emptiness?

When an electron-positron pair vanishes we know that energetic photons of gamma rays are born. But why precisely photons and not something else? That we don't know yet.

When a billiard ball hits another one, we see the interaction as one ball flies off in one direction, and the other moves on. But try to move a stationary ball by sending another ball by in a close miss without touching it. Almost like a horse drawing a cart without being harnessed to it.

In both these cases the bodies interacted due to contact: one ball hitting another, the horse pulling the cart.

Now there is another type of interaction. An apple falls to earth. A magnet attracts iron. Electrified spheres attract and repel. The very word 'attract' indicates that the bodies have begun to interact at a distance.

Maybe this interaction is transmitted through the air. Experiment has long since given a negative answer. The earth attracts the moon, and the sun attracts both, although they are all separated by a practical vacuum. The atomic nucleus attracts electrons, although there is an absolute void between them. All this signifies that bodies can interact without any contact.

A century ago physicists had given the name 'field' to these regions of space in which such action at a distance occurs. But they were not ready to accept the fact that the space between them was empty.

Action cannot occur without an intermediate medium. There simply must be a medium. Accordingly, they conjured up the 'ether' for the extremely tenuous something that permeated all void.

In the course of a number of years, physicists tried to comprehend the properties of this ether, properties which, as you recall our discussion at the beginning of this book, were truly fantastic, even contradictory. Finally, experiments with light at the end of last century put the quietus on the ether concept. Within another few years, Einstein's theory of relativity had demonstrated the complete hopelessness of reinstating the ether in any form or shape whatsoever.

The ether fell, but there was nothing to replace it. Physicists finally gave in and accepted action at a distance in empty space. But how emptiness could be the carrier of interaction was beyond the comprehension of even the greatest minds. Empty space was a void, period.

You certainly said it, the more common sense is relied on, the harder it is to break away. Surely there can be no doubt that space is the repository of all bodies. Isn't that self-evident? A portion of space occupied by matter is called a body, a particle, or what have you. Then there is space not occupied by any matter. This we call a void, empty space, a vacuum. These two portions are not connected in any way. Emptiness does not react on bodies, neither do bodies interact with the void. True, bodies can

interact through empty space, but the void here is of no concern: the interaction is due solely to the bodies themselves.

Emptiness Depends on Bodies!

But then appeared a person who not only became dubious about this, he reconsidered everything from top to bottom. He was Albert Einstein and his theory was called the general theory of relativity. We have already spoken of his first theory, the special theory of relativity, that has to do with fast-moving bodies. The general theory of relativity embraces a much broader problem. In two words, it deals with the relationship of bodies and space.

The principal idea of this theory consists in the statement that matter influences the space around it. Space that is absolutely homogeneous in the absence of bodies (this, of course, is only conceptual space) loses this homogeneity when a body is 'introduced' into it.

How does this happen and how do we measure the inhomogeneity? Geometry does the job. The geometry of empty space is the ordinary geometry of our school days, Euclidean geometry. In this geometry, the shortest distance between two points is a straight line, parallel lines never meet. There are other 'obvious' statements called axioms, which are propositions that are so self-evident as not to require any proof (which, incidentally, is impossible to obtain anyway).

Yet, at the beginning of last century the Russian geometer Lobachevsky saw a flaw in one of these axioms (the parallel axiom). He demonstrated that it was possible to construct a geom-

etry just as noncontradictory, internally, as Euclidean geometry, but quite contradictory to common sense, if one gave up this axiom. So unusual, paradoxical was Lobachevsky's geometry that no one understood it. For many years, Lobachevsky's works collected dust on the shelves of university libraries.

Lobachevsky's contemporaries were shocked by his view that there is no such thing as a geometry 'in general', applicable to all worlds, that each geometry is determined by the properties of the concrete bodies that it deals with, that the geometry of a space depends on the bodies and things existing in that space and on their configurations. Sacrilegious! Man trying to change the god-given geometry of the world!

But in the works of Einstein these notions now found a worthy place. Just as there is no space without bodies, there is no unified homogeneous space. The shortest line between two points in empty space surrounding bodies is now, in the general case, no longer a straight line but a curved line, called a geodesic. The closer the two end-points of our curve are to bodies and the more massive these bodies, the more 'curved' is the curve.

How do we know? Light rays should help us. The curvature of space due to bodies is very slight and under ordinary conditions is not noticeable. We'll have to take the experiment out into interstellar space and choose some massive object, like our sun, as the 'curving' body. It is naturally most convenient to observe curvature in a line which we consider to be straight. If we believe classical physics, this should be a line produced by a ray of light. This is what Einstein set out to refute.

Let us point our telescope at some star and photograph it. Then we photograph it again when its light rays pass close to the sun. The first picture is taken at night, the second, during a total eclipse of the sun.

According to classical physics, both pictures should show the star in one and the same place on the photographic plate. Whether the light passes near the sun or far away from it should make no difference. According to the general theory of relativity, however, the path of light should curve as it passes close to the sun. The photographic plate should exhibit this curvature as a displacement relative to the first picture of the star.

In August 1919, a special expedition set out for the Arabian desert to observe a total solar eclipse. One of its tasks was to verify Einstein's prediction. Sensational news! The photographs showed space to be curved; what is more, the curvature was almost exactly as predicted by Einstein!

From that time on, physicists' concepts of empty space have changed radically. Space has become a repository not only of bodies, but also of fields.

Matter and Fields

What is a field? Physicists use this word to describe space in which bodies manifest interaction. However, there are no noninteracting bodies; all bodies are ultimately made up of particles, none of which are 'indifferent' to the others.

For this reason, fields exist everywhere and at all times. And not only between bodies, but

within them as well, for there, too, there are voids not filled with matter. That is the first and most fundamental property of a field. From this there immediately follows another conclusion: fields are just as real and universal as is matter.

A field is different from matter in one important respect: matter is tangible, the field is not (say, an electric, nuclear, or gravitational field). But we cannot say that it is impossible to perceive a field. Take an apple falling to the ground: the action of the field is evident from the motion of a body.

There is yet another phenomenon displayed by a field—this is light, 'by and of itself'. As early as last century it was established that light is a special so-called electromagnetic field.

In his theory of the photoelectric effect, Einstein introduced the photon. This was an important concept. The electromagnetic field was quantized, which is to say, it existed in the form of individual particles, quanta of the field. The photons were these field quanta.

The history of fields continued to develop. In 1872, Stoletov found that light is capable of exerting material action by ejecting electrons from metal. In 1900, Lebedev discovered the pressure of light on bodies—just as if light consisted of 'real' particles possessing mass.

These two remarkable experiments and the concept of the photon inevitably led to the conclusion that the electromagnetic field has material properties and that field quanta can have the characteristics of particles of matter.

This was the first span in the bridge across the gap between matter and fields. The de Broglie hypothesis meanwhile was building the bridge

from the other end. Electrons could have wave properties. Which meant that matter could behave in a field-like manner.

The field, limitless and imponderable, could have dimensions and mass. Matter, limited in space and ponderable, could be deprived of dimensions and mass.

Should we now conclude that in place of the former sharp distinction between matter and field we must merge them into one indistinguishable entity? No! The material properties of the field are obvious only at large energies of its quanta. And the field properties of matter come to life only at large energies of its particles.

And at low energies? The field is then a field, and matter is matter.

There is no Emptiness!

The photographically detected joint birth of an electron and a positron is not only the 'opening up' of vacuum. This was the first actual case of a field converting into matter. Confirmation soon came of the reverse prediction of Dirac's theory: the joint annihilation of an electron and a positron upon encounter, and the generation (at the same instant) of two gamma photons.

Wait a minute! The electron and positron didn't turn into anything, they vanished unchanged into the vacuum. And the energy they released took the form of gamma photons. Exactly like in, say, an atom where an electron jumps from a higher to a lower energy level releasing its energy in the form of a photon, but at least the electron remains an electron!

Actually, however, this is not quite so. Here it is that the vacuum, the void, appears in its fundamental field-like aspect. In the atom, an electron does give up energy, but only a part of it. It can even lose all its kinetic energy in free motion, it can come to a standstill; but the principal energy (the energy proper) is never given up under any circumstances—that is if the electron wants to remain an electron. For if one gives up an energy $E_0 = m_0c^2$, which is intimately bound up with the rest mass m_0, this is tantamount to losing the rest mass and hence the very essence of being a particle! We have already mentioned the fact that particles differ from the quanta of an electromagnetic field in that they can exist at rest and have a mass not equal to zero.

This means that when an electron dives into the vacuum giving up its joint positron-electron energy proper, it ceases to be an electron, just as the positron ceases to be a positron. Naturally, their mass does not vanish without a trace, just as their energy does not vanish into nothing. The mass changes its nature and becomes nonmaterial, field-like, while the energy proper converts into the energy of field quanta, gamma photons. So the vacuum doesn't have any 'real' electrons after all, they are there conceptually, potentially, so to say.

The reason is that vacuum or void or emptiness is generally nonexistent. Only matter and fields fill all of space. The vacuum that Dirac had in mind was simply a pictorial image to facilitate depicting the processes of the interconversion of particles of matter and field quanta.

The author has not tried to lead the reader about by the nose. He felt that one has to start

with ordinary emptiness and then take up unconventional empty space, and only then cross out both. At any rate, that was the natural path of development of science.

An electron encounters a positron and they convert into gamma-ray photons. If this is possible, then obviously the converse process should be possible: gamma-ray photons converting into particle pairs. This actually does take place provided the photons have sufficient energy, at least $2m_0c^2$.

The photons may be observed, recorded and are quite tangible. The vacuum, on the other hand, is quite intangible until an electron and positron jump out of it. How do we reconcile this situation?

Actually, nothing has to be reconciled. Photons are recorded as photons as long as their energy is not great. As soon as it becomes sufficient for the transformation of a pair of photons into a pair of particles, we begin to feel the 'vacuum' properties of the photons. The photons can vanish with an electron-positron pair taking their place.

The term vacuum signifies the possibility of mutual transformations of material particles into field quanta and field quanta into particles. That is the fundamental point now. And that is what we have been talking about from the very beginning of the chapter.

Apparently, everything is now relatively clear. Since we have bridged the gap between matter and fields, the traffic can move in both directions: particles becoming field quanta and field quanta becoming particles. The important thing is to get up onto the bridge, which is rather high—the energy height measures $2m_0c^2$.

which for electrons signifies millions of electron-volts and for protons, thousands of millions of electron-volts.

To summarize, then, the vacuum has given way to the field. We shall continue to use the term vacuum because of its pictorial nature. It is convenient to picture it as a universal sea with delphine-like particles jumping in and out.

What the Whales Rest on

We can now, finally, explain one of the whales on which the refined quantum mechanics rests. Altogether, there are three whales, like of old: Planck's quantum hypothesis, Einstein's theory of relativity, de Broglie's hypothesis of the wave nature of particles. We shall discuss the latter hypothesis.

I wonder whether it didn't seem a little unjustified what we did just a little while ago—jumping from the general theory of relativity constructed for worlds of astronomical dimensions to the quantum world of ultrasmall things. The point is we have time and again stressed that laws which hold in the world of one scale are at best inaccurate in worlds of other scales. What right had we to extend Einstein's matter and space concepts to the microworld? We have the right, thanks to the de Broglie hypothesis, which has been reliably verified and confirmed. Microparticles have wave properties. This duality of theirs exists everywhere and at all times. But what is a wave? Judging by its properties of indeterminate extension and eternal mobility, it is clearly a field entity. Thus, the de Broglie hypothesis in effect says that material particles

have field properties. In this sense it supplements the Einstein hypothesis, which states that field quanta (photons) have material properties.

How do the field properties of microparticles manifest themselves? We have already encountered numerous instances. Most typical of these properties is the smearedness of electrons and other particles in space. As the physicists say, they are nonlocalized. An electron is here, yet it is not here. In attempts to measure its velocity of motion with exactitude we cease to be able to say anything of its whereabouts. This is very typical of a field; it is impossible to localize a field due to its being 'everywhere'.

If we increase the velocity of an electron, it becomes heavier as we approach the velocity of light. Where does it get its extra mass? Electrons are usually accelerated by electric fields. During acceleration, the electric field enters the electron, as it were, and imparts to it a portion of its energy. Since the energy of the electron is increasing, Einstein's relation (see page 233) says that the electron velocity and mass should also increase.

But this process of 'pumping' mass from the field into the particle cannot go on endlessly. The mass builds up with extreme rapidity and finally the kinetic energy of the particle becomes equal to its energy proper (this occurs when the velocity of the particle reaches about 80 per cent of that of light). At this point, a new process sets in, in which the wave, or field-like, properties of the particles dominate. The particles are now in a position to rid themselves at a single stroke both of the accumulated energy and their proper energy and to convert into quanta of the field.

The reason for the increase in mass of particles with growing velocity is a sort of self-preservation instinct instilled in them by nature. The particles do not wish to lose their individuality and furiously resist any build-up of energy, and the resistance increases as they approach transformation into the field.

Particles can never move with the velocity of propagation of the field. And the field can never propagate with a different velocity.

Particles Change Their Guise

Up till now, particle transformations have dealt only with the electron (and, of course, the positron). After the discovery of the neutron, it was found that it too is capable of transformation, but, unlike the electron, not into field quanta but into other particles.

The neutron can, first of all, convert into a proton, an electron and a neutrino (in beta decay); to do this, it has to be free. In the nucleus, the neutron is converted into a proton and a pi-meson. It was found out later on that the second transformation of the neutron is not very different from the first. A free pi-meson decays into a mu-meson (which is roughly one-fourth as heavy) and a neutrino. In turn, the mu-meson decays into an electron, a neutrino and an antineutrino. We thus have

decay of free neutron:
neutron → proton + electron + neutrino
decay of 'nuclear' neutron:
neutron → proton + pi-meson
pi-meson → mu-meson + neutrino
mu-meson → electron + neutrino
Result: neutron → proton + electron + 2 neutrinos + + antineutrino

However, this arithmetical count of the similarity of the two transformations is largely lost due to the fact that the pi-meson in the nucleus does not decay. We already know that the particles in the nucleus are acted upon by electric forces and by the much more powerful nuclear forces that ensure nuclei their stability.

If there is a new type of force, that means there is a new field. And if there is a new field, that signifies there must be new quanta. The carriers of electromagnetic interactions are photons. By analogy, the carriers of nuclear interactions must be pi-mesons (we have already mentioned that mu-mesons interact with nuclei weakly and therefore cannot be quanta of the nuclear field).

Summarizing, then, pi-mesons are the quanta of the nuclear field. But unlike photons, these quanta have a rest mass, which is rather substantial in the world of ultrasmall things, for it is nearly three hundred times more massive than the electron! For this reason, pi-mesons cannot move with the velocity of light. Some quanta for you! More like particles than quanta, yet they *are* quanta. The harmonious and proportioned picture of the interrelationships of fields and matter that physicists had just described suddenly broke down.

Pi-mesons turned out to be the very limit of duality. They are matter in that they have a nonzero rest mass, they represent a field in that their spin is zero.

Let's think about this for a moment. The point is that after the rise of quantum mechanics physicists established yet another sharp distinction between particles of matter and field quanta. The difference is in the spin. It was found that

'true' particles of matter can have only a spin equal to one-half the Planck constant h (more precisely, $h/4\pi$), whereas field quanta must have spin equal to zero or to an integral number of Planck constants ($h/2\pi$).

There is every reason why spin should exhibit this profound difference in the essence of particles and quanta. It was found that the magnitude of spin exerts an essential influence on the behaviour of microentities.

Recall the Pauli principle, which requires that no two electrons in an assembly can exist in exactly the same states. This goes not only for electrons, but for protons, neutrons, and generally any particles with half-spin.

Now for particles with spin zero or with integral spin this principle does not hold. For instance, in the photon world (practically the whole universe!) there can be any number of photons in the same states, that is, with the same frequency and the same direction of spin (photon spin is equal to unity).

Incidentally, it followed from this division of spins that the mu-meson that physicists first stumbled over could not be the quantum of the nuclear field. It has half-spin. But the pi-mesons all have zero spin and hence can serve as field quanta. But their nonzero rest mass!...

The Two-Faced Pi-Meson

This was a real big surprise to physicists. Let's try to figure it out.

Maybe the neutron is simply a compressed combination of a proton and a pi-meson. No, simple arithmetic will convince us of this: the

rest mass of the neutron and that of the proton are, respectively, approximately equal to 1,839 and 1,836 electron masses, while the rest mass of the electrically charged pi-meson is 273. Which means that when a neutron emits a pi-meson the former should reduce by 273 electron masses and not 3, the way it does.

When a free neutron disintegrates, this problem does not arise. The neutron loses an electron—one electron mass. In addition, it imparts to the electron and neutrino a double proper energy of the electron, after which it acquires the mass of the proton. Now when a pi-meson is emitted, the neutron loses nearly a hundred times more mass, yet for some reason we don't notice it. No one has ever observed neutrons worn out and reduced after the birth of a pi-meson. How come?

But imagine the following picture. A neutron pulls out a negatively charged meson and throws it at a proton which catches the meson and immediately converts into a neutron. The neutron that kicked the meson became a lightweight proton, while the proton that caught the meson became an overheavy neutron. In just no time, the overheavy neutron ejects the meson, again becoming a normal proton, while the lightweight proton picks up this meson and turns into a normal neutron. This ball game consists of two unequal stages, the first is definitely forbidden by all known laws of physics and the second is quite permissible.

The prohibition is due to the fact that no particle can have mass less than the rest mass, whereas we had an underweight proton. This can be expressed in other words: the neutron forward cannot kick a ball heavier than 3 electron masses.

To emit a meson it would have to find some place in its interior the equivalent of 270 electron masses—quite a lot. But this is in direct violation of the law of conservation of energy. Taken as a whole, the ball game does not flout the conservation law, but the first stage of it would seem to.

When this was found to be the case, physicists were inclined to the idea—a bad one indeed—that the law of conservation of energy holds only on the average in the microworld, and can break down in individual events. However, subsequent development of science demonstrated that this law continues to stand firm. The secret of the ball game remains a mystery to classical physics.

However, the fog lifts as soon as we recall that we are dealing with the quantum properties of particles. Physicists gave the name virtual processes to those which are forbidden by the canons of classical reasoning.

A system of particles or a single particle can convert into another system or into another particle in different ways. It is possible that we do not know these routes (which frequently is actually the case), but we are justified in describing the transformation any way we wish, utilizing those intermediate processes which are amenable to calculation today. For the present, virtual processes are convenient pictorial concepts.

Another question: Can a meson be exchanged between a proton and a neutron along the lines of the electron exchange in the hydrogen molecule? This would be much simpler, since electrons do not experience any kind of transformations yet a bond is established between the atoms.

Maybe a negative pi-meson could circulate about two protons.

No, this won't do at all, and here's why. Scientists recently succeeded in hitching up a mu-meson in the atomic cloud in place of an electron, and the mu-meson did the job just as well. For one thing, it joined two atoms of hydrogen into a single molecule (just like an electron does), the so-called mesomolecule of hydrogen. Since the mu-meson is approximately two hundred times more massive than the electron, its cloud of probability is just that much closer to the nucleus, which means that the mu-meson holds two atoms into a molecule 200 times smaller in size.

However, this is not a pi-meson but a mu-meson. And, again, the forces operative in the mesomolecule are not nuclear forces but electrical forces. The latter are much weaker than nuclear forces.

A pi-meson cannot hold its place in the atom like an electron because it strongly and very specifically interacts with the nucleus. The specificity here consists in the fact that the pi-meson converts a neutron into a proton, and a proton into a neutron.

A Clue to Meson Exchange

We can take it that the pi-meson circulates between nuclear particles. However, this circulation is not about the particles, but inside them—by means of the emission of a meson by one particle and its capture by another. But these processes of emission and capture conflict with the laws we have just described. Yet the processes exist. They proceed virtually.

Generally speaking, virtual processes are not new. Recall how microparticles penetrate through potential barriers. From the standpoint of classical theory, the appearance of a particle outside a barrier indicates that it jumped over the barrier. Yet the Schrödinger equation demonstrated the probability that a particle in a well could get outside without acquiring any energy at all. This too seems to conflict with the law of conservation of energy. Actually, to get over the barrier spontaneously, a particle would have to extract energy from itself, and then that energy would have to vanish.

We explained that paradox earlier by invoking the wave properties of the microparticle. Let us recall it briefly.

According to the Heisenberg relation, every particle has an uncertainty of measurement of the value both of kinetic energy and potential energy. Any attempt to catch a particle penetrating through the barrier, that is, to detect it inside the barrier, renders the energy of the particle indeterminate. As a result, this energy becomes such as to permit the particle to jump over the barrier in a classically lawful fashion.

Strictly speaking, in the classical sense we have a breach of the law of conservation of energy. But quantum mechanics demonstrates that there is no violation of the law.

In the very same manner we can explain the emission and absorption of pi-mesons by nuclear particles. The point is that the Heisenberg relation (the one between energy and time) may be applied also to the energy proper of the particle. Then the thinning out of a neutron that has emitted a negative pi-meson, or the loss of a proton upon ejection of a positive pi-meson, and

also the 'fattening' of particles that have absorbed mesons may be regarded as a certain indeterminacy in the energy proper of these particles associated with a certain indeterminacy in their masses.

It is clear that this indeterminacy is no less in magnitude than the energy proper of the pi-meson, $\Delta E = m_{\pi}c^2$, where m_{π} is the rest mass of the pi-meson. From this relation, let us try to find out how long this uncertainty in energy can exist. In other words, how long the total cycle of the 'ball game' between proton and neutron in the nucleus lasts.

From the Heisenberg relation

$$\Delta E \times \Delta t \sim h$$

we get

$$\Delta t \sim \frac{h}{m_{\pi}c^2}$$

Putting into this relation the values of mass of the pi-meson m_{π}, the Planck constant h and the velocity of light c, we get $\Delta t \sim 10^{-23}$ second.

Rather a short time! What distance can the pi-meson cover in this time? There is obviously a limit: the pi-meson can have a velocity only less than that of light. Therefore, the limiting distance covered by a pi-meson from the nuclear particle that emits it is $R = c \times \Delta t \sim 10^{-13}$ cm. But this coincides, in order of magnitude, with the range of nuclear forces! Remarkable! It confirms our reasoning.

Thus, to catch pi-mesons in 'lawless' ejection from nuclear particles and in the same 'lawless' absorption by other particles is impossible for the same reason that we cannot detect electrons during their passage under potential barriers. As soon as we switched on our mental measuring instrument, it would immediately increase the

energy of the proton and neutron (participating in pi-meson exchange) to such an extent that the exchange would be possible in classical fashion.

Again, underlying the virtual process are the wave properties of microparticles! Nuclear forces have a limited range of action for the very reason that the nuclear-field quanta (pi-mesons) have a nonzero rest mass.

The pi-meson exhibits stable conduct only when it is doing duty in the nucleus. In the free state, this particle behaves quite differently. Once outside the nucleus, the pi-meson decays in a very short time, of the order of hundred-millionths of a second. A positive pi-meson converts into a positive mu-meson, a negative one changes into a mu-meson of the same sign of charge. During decay a neutrino is ejected.

Somewhat later a third pi-meson was discovered—an electrically neutral particle. This meson decays a thousand million times faster than its charged brothers. Dying, it gives birth to two gamma-ray photons, but of far greater energy than those produced in electron-positron encounters.

It is this instability of pi-mesons that makes them so different from photons. Photons can change their energy and can even vanish completely in particles giving up their energy. But they never decay. No one has ever observed photons to break up into smaller 'photon-particles' with less energy than their progenitors.

This pi-meson has made quite a mess of the nice picture of field-matter interrelations that physicists had been painting. The pi-meson is certainly the biggest two-faced hybrid of particle and quantum yet!

The Secret of Interaction

Of all the fields known to science today, the electromagnetic field has been studied the most. We know a great deal about the electric field and the magnetic field. The electric field is produced both by stationary and moving charges, the magnetic field, only by moving charges. Since every interaction of charged particles is associated with motion and is manifested in motion, it may generally be stated that every interaction involves the composite electromagnetic field.

For the sake of simplicity, let us disregard the magnetic field for a moment and take a closer look at the electric (more precisely, electrostatic) field. From our school days we remember like charges repulse, unlike charges attract. The textbook explained this mystery as follows: an electric charge creates around it a field, which repulses any like charge that comes into the field, and attracts any unlike charge.

This explanation is no better than saying a person died because some vital force left him.

In school, the word 'force' reduces to the term 'field'. The new term was introduced but was not explained. Field characteristics are also given (intensity, lines of force, etc.) but nothing more is said.

Indeed, although classical physics introduced the concept of field, it was not able to attach to it any specific, exact meaning. The field proved to be so complicated that even today it is largely beyond the range of physicists.

But quantum mechanics has made quite considerable advances here. Let us see just what it has done.

Physics knows two kinds of electric charge—positive and negative. Protons have positive charge, electrons have negative charge. These (and their antiparticles) are the only absolutely stable carriers of charge. We shall now discuss electrons. The proton, it appears, is more complicated and will be taken up later on.

Thus, all negative charges belong to electrons. Let's take two electrons and see how they fight. First of all, they will have to 'learn' of the whereabouts of each other.

The first thought is that each of the electrons will curve the space around it, as Einstein requires of all bodies, no matter how big or how small they are. Then, each of the electron will be in motion in a curve line about the other. Just like a ball rolling along a sheet of paper depressed by another ball at rest on it.

This curvature, however, is due to the mass, not the charge. Accordingly, we have a different field, the field of gravitation.

Second thought: the electron disrupts the homogeneity of the vacuum about it, for if one considers the vacuum as being filled with not yet generated electrons, then our 'epivacuum' electron should be repulsing the vacuum electrons. When our electron gets a partner, the latter will act on the vacuum in similar fashion.

But the repulsion of the real electrons and the vacuum electrons is mutual. The vacuum electrons will do the same with respect to the second electron. This will find expression in the mutual repulsion of both our electrons.

However, if we give it some thought, this reasoning seems a little faulty. We are trying to account for repulsion, yet we introduce it for the real electrons and the vacuum electrons

without any explanation. The horse was changed, but we still stand.

This is true, but the concept of particle interaction via vacuum is fruitful. The only thing we need to assume is that an electron can spontaneously emit photons.

An electron can emit photons. We saw this in electron jumps in atomic clouds. But in the process the electron changed its energy state. True, but what if a free and stationary electron emits a photon and straightway absorbs it back again? Then the energy of the electron will remain the same. And the process itself will be forbidden as far as classical physics goes. But we have seen that quantum mechanics allows such processes, with one proviso: they have to fit into the framework of the uncertainty relation.

The speed with which an electron emits a photon and captures it again should depend solely on the photon energy. The greater the energy of the photon, the faster the electron will complete the operation.

However, during the time the photon is outside the electron it will have time to probe around a bit in the vicinity of its parent. How far out does the neighbourhood reach? To infinity. Remember that the electron can emit photons of any energy, even the smallest. And such photons can move away from their parent to any distance conceivable. However, for photons of a very definite frequency their range of action is of the order of the wavelength of the photon. For photons of visible light, this distance is of the order of a fraction of a micron.

Photons naturally do not confine themselves to the role of observer. If photons emitted by another electron are encountered, they clash.

The result may be that some of the photons will never return to their parents. They may, for instance, be absorbed by a partner.

It would now seem that we have a definite, not virtual, violation of the law of conservation of energy. But no, we haven't. The electron energy will change by exactly as much as is contained in the nonreturning photons, and both electrons will move apart. The farther electrons are separated from each other, the smaller the energy of their interaction.

In the process, the total energy of the photons and electrons remains unchanged, just exactly what it was in the beginning. But of course there never was any beginning or end of the interaction of two electrons. There is no turning off or on of interaction. No matter how far away the electrons are from each other, there will always be some kind of interaction between them.

Still and all, this explanation is not exactly satisfying. The field is somehow attached to its creator, yet we know that photons are extremely independent-acting entities.

Of course, we can, for greater satisfaction, introduce yet another virtual process. We have already mentioned this process, which is actually encountered. A sufficiently energetic photon emitted by an electron can, during the time of its very short permitted life, convert into an electron-positron pair.

This way, in place of one electron we will for an instant have two electrons and a positron. In another instant, the electron will again be by itself. But which one of the two electrons will vanish, merging with the positron? That is impossible to say, since the two electrons are identical.

Extremely interesting, yet too bad that we

can't observe this 'bouquet' of particles emerging from a single electron: everything takes place in too short a time.

But let's check, anyway. A simple calculation with the Heisenberg relation shows that our instant lasts about 10^{-21} second. During this time, the photon was able to give birth to a pair consisting of a second electron and a positron at a distance of about 10^{-11} centimetre from the first electron.

This is exactly the magnitude that is characteristic of the smallest smearedness of an electron in space. 10^{-11} cm is the length of a de Broglie electron wave moving with a velocity close to that of light.

A truly remarkable circumstance! It shows that at the very heart of the wave properties of an electron (and, naturally, of all other particles as well) is interaction—the field of the electron. The electron is smeared because it dives into the vacuum and emerges from it near the same site numberless times every second.

Physicists called this strange electron behaviour the 'trembling electron'. This imagery is very close to reality. In this process, an electron can oscillate while located at any place within the locality appropriated for it. This locality is determined by the energy and, hence, the wavelength of the photons that can generate electron-positron pairs.

The Kingdom of Virtualities

Thus, an electron emits photons virtually. The photons in turn convert, virtually, into electron-positron pairs. The pairs merge giving birth to photons. And the photons are absorbed

by the electron. The entire kaleidoscope of transformations takes place with fantastic rapidity—many millions of millions of millions of times every second.

A photon emitted by some electron may be captured by a different electron. But electrons are all alike, and there is no way of finding out which one captured the emitted photon.

Now the result of this exchange is not virtual, but quite real: electrons strive to get away from each other as far as possible. But even when the distance between them exceeds many times over the degree of their 'vacuum smearedness', photons catch up with them and push them apart still more. But the greater this distance, the less the energetic photons can overcome it, which means that less energy will be imparted to the electrons in photon exchange and the electron repulsion will be more feeble. Which is exactly what Coulomb's law states.

Electronic interaction is all-pervasive. We supposed, for the sake of simplicity, the participation of only two electrons, while actually all the electrons in the universe participate. We might say that the boundless electromagnetic field is found in every corner of the infinite world.

The interaction of an electron and positron, of an electron and proton and, generally, of all differently charged particles has the same virtual nature. But in this case the consequence of photon exchange is not mutual recession but mutual approach of the particles.

Nature is dual.. It deals in the unity of opposites and the opposites of unities, the contrasting of unities. Two particles with opposite charges and the same masses, mirror images, meet as

they jump out of the mirror and cancel their charges and convert into quanta of the field that performs the interaction.

The Virtual Becomes Real

Physicists don't always hit upon the best terms for naming things. 'Virtual' means being in essence but not in fact, not exactly real. Yet a virtual vacuum can suddenly become very real indeed.

Recall the electron transitions in atoms that originate spectra. We have said that these transitions from one state into another are possible only when the probability clouds of the electrons in these states overlap in some portion of space.

The hydrogen atom has two such states whose clouds merge completely. Both of them belong to the second shell, which begins filling up only in the case of lithium. Then there is another state in the first shell, the very lowest, and most stable energy state in which we ordinarily find the hydrogen electron.

To both states (in the first and second stories of the atomic building) there correspond spherical clouds that never overlap. The third state that we have in mind is an inconvenient interstorey flat connecting the first and second stories.

But it becomes interstorey only in the case of lithium, whereas in the hydrogen atom it has to coincide with the flat on the second floor. And the electron transition that could be observed in the case of lithium should not be observed in the case of hydrogen. The atomic inhabitants do not ordinarily jump directly between sto-

ries, but prefer to get into interstorey flats first.

Indeed, in the hydrogen atom nobody has ever observed such transitions. If for some reason an inhabitant on the first floor is tossed up to the second, he will remain there quite alone until some 'unlawful' circumstance returns him (the probability of such a transition is utterly negligible).

But some fifteen years ago physicists noticed that the electron had succeeded in getting around this very stringent prohibition and rather easily got back to the first floor from the second. Almost like coming down in a lift.

This violation was soon accounted for. A fertile imagination was all that was needed. And physicists are certainly imaginative. Recall the virtual process in which a real electron repulses the 'unborn' vacuum electrons. At that time it seemed that the electron was fighting its shadow.

This is what happens. The interaction of electron and vacuum, the 'trembling' of the electron imparts to it a very real, though small, additional energy. But even this negligibly small energy (much less than that of the electron in the atom) is sufficient for the two merged states in the hydrogen atom to separate, for the electron to pass from one of these states into another, from the second floor to the now real interstorey flat, and from there into the first storey.

True, it was possible actually to detect only the transition from the second floor to the interstorey flat. But that was enough since the rest goes by itself.

What was the vacuum addition to the energy of the hydrogen electron? If we use the Planck

relation and convert it into frequency, then it will come out not among the gamma rays or even those of visible light, but in the high-frequency radiowave band.

That was why this remarkable phenomenon could not be discovered by conventional spectral methods. But when high-frequency radio oscillators were built after World War II and hydrogen atoms were irradiated with high frequencies, they immediately responded to the frequency that fits the vacuum addition. A deep dip appeared at the site of this frequency in the 'radio-spectrum' of hydrogen—the hydrogen electron was actively absorbing quanta on this frequency.

A little while later a second vacuum effect was discovered. We have already spoken about the two electron magnets. One of them was due to the motion of the electron about the atomic nucleus, the other was caused by the spin motion of the electron. In a magnetic field, these two magnets combine into a sort of unified magnet of a definite magnitude.

Physicists measured the force of this elementary magnet with great exactitude. And it was found to be just a little bit greater than the sum of the two together. Again that 'just a little bit'. The only thing left for physicists was to acknowledge that this addition in the magnitude of the magnet is due to the interaction of electron and vacuum.

The, explanation is again similar to what we have already given. An electron moving in an atom repulses the vacuum electrons all along its path, as it were, like a stationary ship only displaces water, while a moving vessel makes the water move as well. The transfer of motion from the electron to the vacuum is what produces

in the latter a current of vacuum electrons. The magnetic effects of virtual current are added to those that correspond to the motion of the 'real' electron.

Quantum mechanics, which is permeated with virtualities, was not only able to account for these remarkable phenomena, but to calculate them, as well; and the results coincided beautifully with experiment!

There you are, the physicist and his imagination! Virtual processes are something to be respected after all.

In the Search for New Particles

As soon as physicists accepted the unusual nature of the world of microparticles, their interrelations among themselves and with the field, a real hunt began for new particles. Every new particle is a new aspect of the microworld, a new discovery of its peculiarities, an advance on the path of knowledge.

Whole expeditions were on the go, with intricate gear, equipment and instrumentation. For a long time, the cosmic rays—those streams of particles coming to earth from deep space—were the only suppliers of new particles. New instruments were invented, old instruments were refined and fresh expeditions set out to mountain peaks, up into the clear air closer to the sky, others put out to sea, and still others sent up rockets to new heights. And the results came in avalanches, nearly every year saw the discovery of dozens of new particles!

The first to react were the theoreticians. They were worried in a real way, for, they said, there

just couldn't be so many different particles! Experimenters reviewed their results with an extracritical eye. Then the 'new' particles began to disappear one after the other, faster than they had come onto the scene.

Yet the booty was impressive. Pi-mesons were the first. At the beginning of the fifties, particles were discovered that were more massive than protons and neutrons; they were called hyperons. Cosmic radiation presented physicists with a very valuable gift, a group of K-mesons (we will soon see why it was so valuable).

And when a series of gigantic accelerating machines were put into operation racing protons to close-optical velocities, two new particles were discovered that confirmed the predictions of Dirac's theory. They were the antiproton and the antineutron.

Today, the whole list of microparticles is truly impressive. There are about thirty different types—about 25 years ago there were only four. And these are all very real particles.

Let's take a look at the list. The first thing one notices is the broad range of masses: from the electron mass to two and a half thousand electron masses in the case of the xi-hyperon. The distribution of particles as to mass is rather uneven. They come in groups of two and three with similar masses.

Now the charges and spins don't show any sign of diversity. Particle charges can have three values (+1, 0 and −1, where −1 is the charge of the electron); the spins have three values as well (1, $^1/_2$, and 0 in Planck units $h/2\pi$). Finally, most of the particles in this list are unstable: on the average they have lifetimes ranging from millionths of a second (mu-mesons)

Class of par cle	Name	Designation	Mass (in electron masses)	Charge	Spin (in Planck units $h/2\pi$)	Lifetime in seconds	Decay scheme
Leptons (light particles)	Photon	γ	0	0	1	Stable	
	Electron	e^-	1	-1	1/2	ditto	
	Positron	e^+	1	$+1$	1/2	ditto	
	Neutrinos 1 and 2	ν	0	0	1/2	ditto	
	Antineutrinos 1 and 2	$\overline{\nu}$	0	0	1/2	ditto	
	Mu-minus-meson	μ^-	206.7	-1	1/2	2.2×10^{-6}	$\mu^- \to e^- + \nu + \overline{\nu}$
	Mu-plus-meson	μ^+	206.7	$+1$	1/2	2.2×10^{-6}	$\mu^+ \to e^+ + \nu + \overline{\nu}$
Mesons (medium particles)	Pi-minus	π^-	273.2	-1	0	2.6×10^{-8}	$\pi^- \to \mu^- + \overline{\nu}$
	Pi-plus	π^+	273.2	$+1$	0	2.6×10^{-8}	$\pi^+ \to \mu^+ + \nu$
	Pi-zero	π^0	264.2	0	0	2.2×10^{-16}	$\pi^0 \to 2\gamma$
	K-minus	K^-	966.5	-1	0	1.2×10^{-8}	$K^- \to 2\pi^- + \pi^+$ or $2\pi^0 + \pi^-$

(*Cont'd*)

Class of particle	Name	Designation	Mass (in electron masses)	Charge	Spin (in Planck units $h/2\pi$)	Lifetime in seconds	Decay scheme
Mesons (medium particles)	K-plus	K^+	966.5	+1	0	1.2×10^{-8}	$K^+ \to 2\pi^+ + \pi^-$ or $2\pi^0 + \pi^+$
	K-zero	K^0	974.2	0	0 K_1^0	1.0×10^{-10}	$K_1^0 \to \pi^+ + \pi^-$ or $2\pi^0$
	Anti-K-zero	$\overline{K}^0$	974.2	0	0 K_2^0	6.1×10^{-8}	$K_2^0 \to 3\pi^0$
Baryons (heavy particles): Nucleons (nuclear particles)	Proton	p	1,836.12	+1	1/2	Stable	
	Antiproton	$\overline{p}$	1,836.12	−1	1/2	ditto	
	Neutron	n	1,838.5	0	1/2	1.0×10^3	$n \to p + e^- + \overline{\nu}$
	Antineutron	$\overline{n}$	1,838.5	0	1/2	1.0×10^3	$\overline{n} \to \overline{p} + e^+ + \nu$

(Cont'd)

	Class of particle	Name	Designation	Mass (in electron masses)	Charge	Spin (in Planck units $h/2\pi$)	Lifetime in seconds	Decay scheme
Baryons (heavy particles)	Hyperons (large particles)	Lambda-zero	Λ^0	2,182.8	0	1/2	2.5×10^{-10}	$\Lambda^0 \rightarrow p + \pi^-$ or $n + \pi^0$
		Anti-lambda-zero	$\overline{\Lambda}^0$	2,182.8	0	1/2	2.5×10^{-10}	$\overline{\Lambda} \rightarrow \overline{p} + \pi^+$ or $\overline{n} + \pi^0$
		Sigma-plus	Σ^+	2,327.7	+1	1/2	8.1×10^{-11}	$\Sigma^+ \rightarrow n + \pi^+$ or $p + \pi^0$
		Anti-sigma-plus	$\overline{\Sigma}^+$	2,327.7	—1	1/2	8.1×10^{-11}	$\overline{\Sigma}^+ \rightarrow \overline{n} + \pi^-$ or $\overline{p} + \pi^0$
		Sigma-zero	Σ^0	2,331.8	0	1/2	$<10^{-11}$	$\Sigma^0 \rightarrow \Lambda^0 + \gamma$
		Anti-sigma-zero	$\overline{\Sigma}^0$	2,331.8	0	1/2	$<10^{-11}$	$\overline{\Sigma}^0 \rightarrow \overline{\Lambda}^0 + \gamma$
		Sigma-minus	Σ^-	2,340.6	—1	1/2	1.6×10^{-10}	$\Sigma^- \rightarrow n + \pi^-$
		Anti-sigma-minus	$\overline{\Sigma}^-$	2,340.6	+1	1/2	1.6×10^{-10}	$\overline{\Sigma}^- \rightarrow \overline{n} + \pi^+$
		Xi-zero	Ξ^0	2,565	0	1/2	1.5×10^{-10}	$\Xi^0 \rightarrow \Lambda^0 + \pi^0$
		Anti-xi-zero	$\overline{\Xi}^0$	2,565	0	1/2	1.5×10^{-10}	$\overline{\Xi}^0 \rightarrow \overline{\Lambda}^0 + \pi^0$
		Xi-minus	Ξ^-	2,580.2	—1	1/2	1.2×10^{-10}	$\Xi^- \rightarrow \Lambda^0 + \pi^-$
		Anti-xi-minus	$\overline{\Xi}^-$	2,580.2	+1	1/2	1.2×10^{-10}	$\overline{\Xi}^- \rightarrow \overline{\Lambda}^0 + \pi^+$

to thousands of millions of times smaller fractions of a second (pi-zero-mesons). These two lifetimes are the extremes. In the middle of the range are unstable particles with lifetimes from hundred millionths to ten-thousand millionths of a second.

Don't make the mistake of confusing the lifetime of a particle with the time of its existence in our world. As an illustration, take the positron. It is stable in the sense that it does not decay into any other particles. Yet it doesn't live long in our world—as soon as it meets an electron, it vanishes, as a rule. On the other hand, pi-mesons which are unstable in the free state, never decay within nuclei.

Look at the last column of the Table. What are the particles that most often appear in the decay products of their unstable brothers? These are electrons and neutrinos for mesons and the neutron. And we always find nucleons and pi-mesons among the decay debris of hyperons.

Sorting the Booty

These are the first preliminary conclusions that we can draw from a census of the microworld. Now the problem is to figure out what the living conditions of particles are like in the microworld.

Why the great diversity in particle masses? What is the limiting mass? Is it the heavy xi-minus-hyperon? Why do particles exhibit groups of closely related masses of two, three and four particles? Why does the charge of particles have only three values and the spin, two (if we disregard the photon)? Why are most particles unstable? Why, again, are there stable

particles? Why do particles choose only one or two of a large variety of possible decay schemes?

Before going any further it must be said that quantum mechanics has left most of these questions without answers. And where there are answers, most of them describe 'how', but don't say 'why'. Which is something at least.

The grouping by mass is clearly seen in the Table. The particle masses in one group are very close to one another if compared to the broad interval that separates one group from the next. This has been accounted for in an interesting way: a group of particles is actually only a single particle that appears in different guises.

By way of illustration, let us take the pi-mesons. The masses of the pi-minus- and pi-plus-mesons are equal and differ from the mass of the third, electrically neutral, pi-zero-meson. Maybe the higher mass of the charged particles is due to their having charge.

We have already mentioned the fact that the field accounts for a portion of the mass of a particle. Since pi-mesons are the quanta of the nuclear field, and this field is very much stronger than the electromagnetic field, it would be reasonable to suppose that the bulk of the mass of pi-mesons is due to the nuclear field, while any addition to it of the electromagnetic field (associated with the presence of charges) would make only a small contribution. For this reason, charged pi-mesons are more massive than the neutral particle, which naturally should be of nuclear origin entirely.

This would likewise appear to account for the fact that lightweight particles do not form triplets. The nuclear field differs in that its quanta have nonzero rest mass, whereas the quanta of

the electromagnetic field are photons with zero rest mass. The electron and positron and both mu-mesons are of a pronounced non-nuclear, electromagnetic origin. That explains why they have no neutral particle. This leaves two possibilities: a positive and a negative particle, a doublet.

This doesn't work for K-mesons. The neutral K-meson is more massive than the charged particles. Here the electromagnetic field would seem to be 'subtracted' from the nuclear field.

That is why physicists are inclined to accept this explanation as simply a conjecture. Hyperons, which are of nuclear origin and have no triplets, seem to confirm this. Here too we are still lacking any explanation.

Antiparticles Come into Action

Up until 1955, the nucleon group consisted only of the proton and the neutron. This was quite a team: a doublet made up of a charged particle and a neutral particle! The mystery was resolved, so it appeared, when the negatively charged antiproton was discovered, for here was now a normal triplet like the group of pi-mesons.

True, there was one inconvenience: the neutral neutron was heavier, not lighter, than the proton and its antiparticle. Again the electromagnetic field appeared to be 'subtracted' from the nuclear field. Most important, however, was the fact that the proton and neutron turned out to be a single particle in two forms. Incidentally, physicists had guessed as much when it was clear that the two particles interconverted in the nucleus with equal ease.

But then a year after the discovery of the antiproton, the antineutron was uncovered. A fourth particle in one group. The antineutron didn't want to fit into the group scheme. There was still one way out—the nucleon group could be viewed as made up of two pairs: proton and neutron with their antiparticles. But then the proton and the neutron would be two distinct particles. That was a hard nut, and it's still uncracked today—the secret of the quadruplet of nucleons.

Similar to this group are the four K-mesons. That will be a special talk. Finally, we note that the hyperons only come in pairs.

Is there any law underlying this group structure of particles? There very easily could be, but we don't know it. The census of the microworld is done and over, distributions have been made as to occupation, but no final conclusions can yet be drawn.

Now let us try to figure out the difference between a particle and its antiparticle. As we know, the Dirac theory in its original form stated that the difference was in the sign of electric charge, which is true enough for the electron and positron, the proton and antiproton, the two mu-mesons and, in general, for all charged particles.

But how about the neutron and its antineutron? There is no electric charge and their masses are the same, as in all particle-antiparticle pairs. The difference here, it appears, is in the sense of the magnetic moment.

Then this too can be an 'antiproperty'? Well, we know that electrons in atoms occupy energy states in teams of two, which means they have opposite spins. Yet the particles remain electrons,

14—2

not one of them changes into a positron. Also, nuclear neutrons, as we recall from the shell model of the nucleus, can occupy energy levels two at a time, and no antineutron is born.

That the spins of atomic electrons are oppositely directed in pairs only means that the electrons themselves are moving in opposite directions. If electrons are pictured as 'clouds of probability', two opposite directions are of course difficult to conceive. For a free atom, they do not differ in energy. But electron spin is definitely orientated with respect to the direction of motion. For instance, if an electron is moving to the right, we may say that its spin is, for instance, directed at some angle upwards; if the movement is to the left, then downwards. It may be shown that as the velocity of the electron approaches that of light, the direction of its spin comes closer and closer to that of its motion. In the case of the positron, the situation is reversed. For a very fast positron, the spin is almost counter to the direction of motion. That is the way we understand the difference in direction of magnetic moments in the case of the neutron and the antineutron.

The reader may be disappointed with 'differences' of this kind, but it seems to be enough to make the particle and antiparticle vanish, upon encounter, into field quanta.

Particles Disintegrate

How do particles originate and vanish? Photographic plates are the first to witness these events of the microworld which mean so much to scientists.

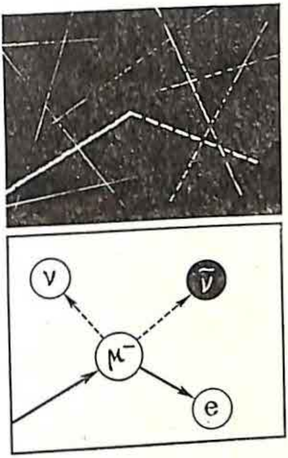

Fig. 25.

Here in the corner of the plate is a thick mu-minus-meson track. Before even reaching the middle of the plate it 'breaks' and goes off in a dashed line. This portion of the track belongs to an electron. At the breaking point, two particles were born which carried off the energy and momentum of the mu-meson that was not imparted to the electron. These two particles are a neutrino and an antineutrino.

As a rule, pi-mesons do not decay into electrons directly. They first generate mu-mesons. Here, too, we see that the nuclear field and the electromagnetic field are not completely separate. A particle of nuclear origin converts into a particle of electromagnetic nature.

Why do pi-mesons disintegrate into two particles, and mu-mesons decay into three? The

answer is simple: it's all due to the spin. The sum of the spins of the daughter particles must equal the spin of the parent particle.

The mu-meson has half-spin, the electron also. But since the electron cannot carry off the entire mass of the mu-meson, a neutrino is needed, which takes up the residue of mass in the form of energy of motion. But the neutrino spin is also one half, so that now the total spin of the newly born particles is greater than the spin of the parent. The neutrino must now get rid of the extra spin. This is the antineutrino with opposite spin. The result: three particles.

In the decay of a pi-meson, one neutrino (or antineutrino) is enough with spin counter to that of the parent mu-meson. These spins cancel, yielding zero, which is equal to the spin of the original pi-meson.

In the case of hyperons, the ultimate stable product of their decay is frequently the proton. In addition, hyperons emit pi-mesons. Two worlds and two limiting types of transformations: the electron in the light particles, the proton among the heavy particles. Two worlds and two inevitable decay satellites: the neutrino in the case of light particles, and the pi-mesons in the case of the heavy particles.

Now is there any law that states which one (or, at most, two) of a number of decay schemes is to be utilized?

We have already noticed certain peculiarities of such selectiveness. By analogy with classical physics, let us call them conservation laws. Observations show that the total charge and total spin of a particle are conserved in decay. But still these laws leave a little latitude in the choice of the decay scheme.

There ought to be some other decay laws that would narrow down the pathways that unstable particles can follow for conversion into the stable building stones of matter—the proton and the electron.

Physicists Classify Interactions

Let's begin with an analogy. There are different ways of destroying a mountain. One is in an explosion, say a volcanic eruption. Another, weaker and slower, is by an earthquake. And, finally, the slowest of all is weathering—by the work of water, wind, heat and cold. The explosion does the job in seconds, the earthquake in hours, and the water and wind in many thousands of years.

Studies of the processes of destruction of microparticles showed up three types that proceed with different strength and at different rates.

The first, the strongest, occurs in collisions of nuclear particles, in interactions in the nucleus. Physicists called these events strong interactions. They are typified by large energies of the order of the energy proper of the pi-meson and higher, and, accordingly (by the uncertainty relation) very short lifetimes. As we already know, the time factor here is of the order of 10^{-23} second.

The next in strength and duration is electromagnetic interaction. It is in this process that electron-positron encounters produce two gamma photons. In this class too is the above-described decay of a neutral pi-zero-meson into gamma photons. This process has a duration of the order of 10^{-17} second.

Now, finally, the weakest and longest process of all. Physicists call it weak interaction. It is this process that is responsible for the great majority of decays given in the Table of microparticles. Weak interaction accounts for the decay of mu-, pi- and K-mesons, the neutron and hyperons. From the Table it may be seen that the duration of this 'universal' destructive interaction that affects particles in all groups is 10^{-10} second and more.

An interesting thing was noticed in these studies of groups of particles. The K-mesons and hyperons grouped together in a different way from that of the other particles.

These two groups did not want to fit into the classification of the other particles. "Strange," said physicists, and, chagrined, they called these unruly objects 'strange particles'. They even introduced a special quantity to describe quantitatively the degree to which they deviated from the properties that they should have had. The quantity is known as 'strangeness'.

It was found that strange particles cannot decay into ordinary particles other than by the slow weak interaction. In collisions of ordinary particles, strange particles are born only in pairs, and only in such pairs whose sum of strangenesses is equal to zero, like the original, ordinary particles.

In other words, in strong and electromagnetic interactions the strangeness does not change. This became known as the law of conservation of strangeness. But in weak interactions this law does not hold.

Too many laws? Where is that single general law? And how do we account for them all, anyway?

Unfortunately, the regularities we have been talking about do not as yet have any cogent explanation. Physicists combine these rules this way and that, but the deep underlying essence is still obscure. True, the arithmetic of the conservation laws has enabled us to solve the problem that we started out with. All the rules taken together leave the particles actually only one, at most two, schemes of decay.

Studies of the decay of K-mesons made possible one of the biggest discoveries in the physics of microparticles after the detection of vacuum effects. The two words that shook the scientific community of the world are 'nonconservation of parity'.

The Mystery of the K-Mesons

K-mesons were discovered in cosmic rays some ten years ago. Among the mass of bizarre tracks that cosmic particles leave on photographic plates, the vigilant eyes of physicists discerned the traces of certain new particles with masses roughly a thousand times more than the electron mass.

There turned out to be three kinds of K-meson: positive, negative, and neutral. The spin was determined and came out equal to zero. At first the family of K-mesons did not seem to differ much (with the exception of mass) from the lighter family of pi-mesons: the same zero spin, the same triplet of particles, only the neutral K-mesons were heavier than their lighter cousins.

Physicists scrutinized the tracks left behind by K-mesons on photographic plates. The charged particles produced ordinary tracks that

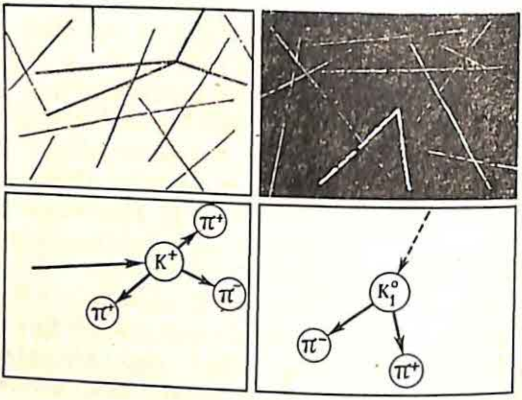

Fig. 26.

frequently terminated, giving way to thin tracks. What this meant was that the K-mesons had decayed into lighter particles. A study of the secondary tracks showed that they belonged to pi-mesons.

The decay of the neutral K-mesons was more difficult. Physicists were surprised to find two tracks, and sometimes three, coming out of the end-point of the K-meson flight path. As before, all these tracks belonged to pi-mesons.

Thus, neutral K-mesons sometimes decayed into three and sometimes into two pi-mesons, while all the other particles always disintegrated into the same daughter particles in one way only.

The experimenters were sure it couldn't be otherwise, and so they decided to introduce two different neutral K-mesons. One of them was christened the tau-meson, the other the theta-meson. Two different mesons for the two distinct

schemes of decay. That seemed to be clear enough.

But physicists were not satisfied. The most careful measurements invariably indicated that the tau-meson and the theta-meson had identical masses. Throughout the Table of particles this always meant one thing: identical particles. But one and the same particle cannot, surely, decay first into two and then into three identical daughter particles!

That was the mysterious particle of the physics of the early 1950's. The famous 'tau-theta' enigma.

But what, after all, is so strange? Why can't the K-meson decay as described? The law of conservation of energy does not forbid it, the conservation laws of momentum and spin have nothing against it.

Yet it is forbidden by a law that we have not yet mentioned. This prohibition was established by quantum mechanics and goes by the name of the law of conservation of parity.

Is the Left Any Different from the Right?

Recall the emission of photons by excited atoms. An electron was in one state, then it jumped into another, of less energy. At that time we were interested only in the energy and whether the 'clouds of probability' of the initial and terminal states of the electron overlapped.

This overlapping seems to be very essentially related to parity. If we could renumber the flats in the atom, we would find that the inhabitants can only move from even to odd flats and vice versa. To move from the tenth flat, say

to the eighth in a single jump is impossible.

This rule, which was experimentally established as far back as 1924, was later given a quantum-mechanical interpretation. To do this, physicists introduced the notion of parity of the wave function. From there the concept of parity was extended to the state itself as described by the wave function.

The wave function we know: it is the solution of the Schrödinger equation. Parity now requires a little more discussion.

How many people, when looking at their photograph, say: "Oh, but that doesn't look like me at all." And the photographer is to blame. But quite often he really shouldn't be.

Take a look at yourself in the mirror. What you see is not an exact copy. If your nose bends slightly to the right, the mirror will show it inclined to the left. In a mirror, right and left change places.

When you have your picture taken, the front side of the film shows your mirror image. But this is not all. The film is developed, and the negative is made into a picture, which is actually another reflection of you in a mirror. Sometimes, when the picture is made, the negative is turned upside down so that we then get three mirror reflections. But sometimes the negative remains in the same position as when the picture was snapped, and then there are only two such reflections.

A person always looks like he appears in a mirror. But a photograph can make you the way you actually are and not the way people see you.

The photographic and mirror images would coincide only in the ideal case of a person with

an absolutely symmetrical face. But that is rare indeed. Nature likes pure cold symmetry, but never begrudges a bit of variety.

The essential thing here is that a double reflection always restores the original shape of an object, irrespective of whether there is symmetry or not. Something like two minuses make a plus and two pluses make a plus. In a double reflection in a mirror, the 'minuses' of your face (asymmetry) do not distort the image.

Wave functions possess the same peculiarities. These functions are ordinary mathematical functions, among which we frequently find sines and cosines. Draw them on paper and put them up to a mirror. The sine, in the mirror, is upside down. Which is nothing new: in school trigonometry we know that the sine of a negative angle is equal to the sine of a positive angle with sign reversed. Our mirror, as it were, extends the axis of angles in the direction of negative values. Now the cosine will not change in the mirror. And trigonometry confirms this.

Mathematicians called the cosine an even function and the sine, an odd function. The mirror reflection was also given a name: space inversion. And to distinguish even functions from odd ones, they were given signs: plus for even, minus for odd.

If a sine reflected in a mirror is viewed in a second mirror, the original shape will be restored, for a minus times a minus yields a plus. The cosine will of course remain unchanged.

An investigation of the solutions of the Schrödinger equation showed that for atomic electrons the parity never changes in jumps to new states. If the wave function of an electron was first even and then after a jump to another state

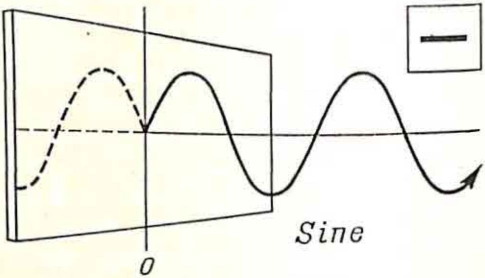

Fig. 27.

became odd, this would signify only one thing—the wave function of the photon generated in the transition is odd.

Later, the concept of parity was extended from atomic states to separate particles. The photon was the first; later, labels appeared on the other particles as well. The electron, for instance, proved to be an odd particle.

We have occasion to say that the spin of an electron is very definitely oriented relative to the direction of motion of the particle. If the electron is in motion rightwards, its spin is, say, upwards; if to the left, then the spin is downwards. Let us try, mentally, to reflect an electron in a mirror. We see that as the electron moves to the right (to the left in the mirror), its spin in the mirror remains in the upward direction because the mirror only interchanges right and left, but does not turn the image upside down. The mirror electron has a direction of spin that is nonexistent in the normal electron. Which means that the electron is definitely an odd particle. If it were even, the mirror image would not differ from the real thing.

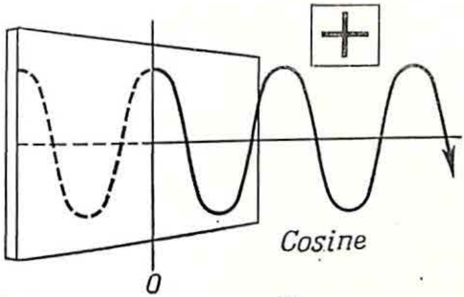

Fig. 28.

The pi-meson is an odd particle.

Extending their classification of parity to the unstable particles, physicists, working by analogy with the emission of a photon by an electron, established that the parity of the initial particle must be equal to the product of the parities of all decay particles produced. So far, particles have never violated this injunction which goes by the name of the law of conservation of parity.

And now we have the neutral K-meson! Judging by the fact that it decays into two pi-mesons, this is an even particle (a minus and a minus produce a plus). Yet its decay into three pi-mesons indicates that this particle is odd (a minus times a minus times a minus yields a minus). What is it in reality, even or odd?

It is clear that we are dealing with one and not two particles: the masses of the tau- and theta-mesons coincide too closely. But then the K-meson is a particle with double parity! No, that would be too much to presume. This K-meson has certainly got quantum mechanics in a hole.

A Way out is Found!

What is there to do? To say that parity breaks down in the decay of neutral K-mesons would mean that nature uses a faulty mirror, where the left differs from the right, where space itself is not symmetrical! That would be a terrible conclusion.

During the long years of its existence, physics is used to the fact that space is the same in all directions. Movement to the left, under identical conditions, is in no way different from movement to the right. True. All the laws of physics point to the equivalence of directions, called the isotropy of space.

To give this up would mean rejecting all the most basic and fundamental of physical laws. Terrible even to think about.

The young physicists Li and Young found a remarkable way out of this impasse. They boldly stated: yes, parity can break down in the decay of K-mesons and, generally, in all weak interactions (which give rise to the decay of mesons and the beta decay of nuclear neutrons)!

Li and Young pointed to experiments that would unambiguously establish this amazing fact. They are worth describing.

Calculations showed that if the parity did break down, then in nuclear beta decay the electrons should fly out mostly in a direction opposite that of nuclear spin. Under ordinary conditions, the nuclei orient their spins randomly and electrons come out in all directions.

So the first thing that had to be done was to line up the nuclei so that all their spins would be in one direction, and then to keep them lined up during the experiment. To do this, a piece

of beta-radioactive material was put in a strong magnetic field that kept the spin magnets of the nuclei aligned. Then the temperature was drastically lowered (to only five hundredths of a degree above absolute zero) to eliminate the distorting effects of thermal motion of the nuclei.

Then a series of electron counters were arranged around this set-up at a slight angle to the direction of nuclear spin and in a mirrored direction to it. The counters were switched on and it was soon found that there were fewer electron counts in the forward direction than in the 'mirror' direction. The Li-Young prediction was verified.

Did this mean that space was a distorted mirror of nature? And the fundamental laws of physics go topsy-turvy? Here, Li and Young, and, independently, the Soviet physicist L. Landau made an important statement: space had nothing to do with it, the fault was with the particles themselves.

You remember how we reflected an electron in a mirror and obtained a nonexistent electron with reversed spin. Now, it turns out, this particle does indeed exist, but we have to 'reflect' (reverse) its electric charge as well. Then we get an exact reflection of the electron—the familiar positron!

Nature's mirror is all right, after all. But it is a sort of a dual mirror: when a particle is reflected in it we always get its antiparticle! The electron gives rise to the positron, the neutral K-meson gives birth to the neutral, but anti-K-meson.

The neutral K-mesons that were experimentally observed proved to be a mixture of two kinds:

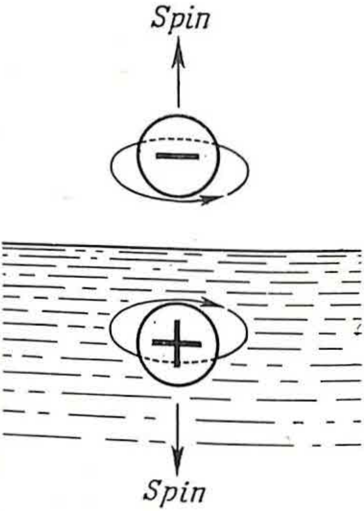

Fig. 29.

the K-zero-meson and its antiparticle. But the K-zero-meson is odd, while its antiparticle is even. That is the 'tau-theta' mystery cleared up.

Credit for the discovery of this double type of reflection, called 'combined inversion' in scientific jargon, goes to Li and Young. The same discovery was made independently by Landau.

Thus it was definitively established that the spin of a particle could be oriented relative to the direction of motion of the particle only in some definite way, and it must be opposite to that of the antiparticle. If we assume, for a moment, that the spin is actual self-rotation of the particle, then the picture is like this. Tag the surface of the electron and follow it during the motion of the particle by means of high-speed mental cinematography. We will

see that the label describes a spiral: in the case of the electron, there will be a leftward twist, in the case of the positron, a rightward twist.

Actually, the difference in 'spiralness', or helicity, is what distinguishes particles from their antiparticles. Bear in mind, however, that the notion of right and left is just as relative as that of positive and negative. We simply agree to giving particles left-hand helicity and antiparticles, right-hand helicity.

Worlds and Antiworlds

We have already mentioned the fact that in our world positrons are rare guests. This would suggest that the world of particles is not symmetrical, left-hand helicity being encountered much more often than right-hand helicity.

This should not be surprising. Just take a closer look at the world of big things. The snail has left-hand helicity more often, the shell spirals leftwards. In chemistry we have stereoisomeric molecules, which are the mirror images of one another. And in their world, too, we find either more left-hand or right-hand isomers. Finally, in human beings the heart is on the left, though very occasionally we find 'mirror' people with all the internal organs switched around. Lefties are rather common, yet most people are right-handed.

We shouldn't be surprised, then, that in the bigger world of space we might find antiworlds, in which everything is reversed. There, antiatoms would have antinuclei made up of antiprotons and antineutrons surrounded by positrons. There,

the living organisms, if there are any, would be the mirror image of our earthly beings.

If both worlds live under identical conditions, the laws of the antiworld should not differ in any way from those of our own world. But in each case the sign would be reversed. That is why we would never know of the existence of an antiworld, even if it were right next to us.

The only thing we could find out about would be the boundary line between the ordinary world and the antiworld. Here the two meet, and there would never be more hostile encounters, for the particles would vanish into energetic gamma photons flying out in all directions from the point of clash with the speed of light or they would convert into pi-mesons. Photons and pi-mesons would sort of belt off the two worlds indicating the danger zone for any particle that might be thinking of darting over to the opposite world. So far, scientists have no indications of any such boundary line in our solar system or in the much vaster stellar system, for that matter.

What Goes on Inside Particles?

We'll start with the question that was never answered: What are the exact dimensions of microparticles? Do these particles have exact dimensions at all?

What a question! Surely everything has some kind of size. Well, not so surely, especially after what we've gone through.

For a very long time physicists were not able to attack this problem properly. Partly that was because the mathematical apparatus of quantum mechanics failed as soon as particles

were endowed with dimensions. On the other hand, as we have already seen, there is no way of actually measuring their size. This is due to the wave properties that smear out the particle in space.

These wave properties are an external manifestation of the interrelations of particles with their fields. In other words, an electron is smeared out due to its interaction with other particles, including electrons.

We know what the modern picture of this interaction is. An electron in virtual fashion emits photons and interacts with photons emitted by other particles. The result is either mutual repulsion or attraction of the particles. The electron is, as it were, wrapped up in a cloud of virtual photons which it is emitting and absorbing. This cloud is boundless: there will always be low-energy photons such that the Heisenberg relation will allow them to go to any distance from the electron that emitted them. It is the photon cloud which smears the electron out in space that does not allow us to speak of exact dimensions.

Still, the cloud rapidly contracts as it approaches the core. At distances where virtual photons have energy enough to form electron-positron pairs (it is of the order of 10^{-11} cm) we have what might be called a 'trembling' electron. The electron is still smeared out, yet over a smaller region of space. Again there are no exact dimensions.

Maybe it would be possible to measure exactly the size of a 'bare' electron, rid of its photon and electron-positron clouds. No, that is impossible for there is no such thing in nature as a noninteracting electron. It simply does not and

cannot exist. The particle and its interaction are two things that form a unity, an inseparable unity!

The only thing left for us to suppose is that inside all these clouds is something in the nature of a 'core', as physicists have termed it. But today we know nothing definite about what this core looks like and of what goes on inside it.

Physicists have tried to do a similar job in describing the structure of another fundamental particle, the proton. The proton emits (in virtual manner) pi-mesons with energies that are naturally not less than their rest energies. That is why pi-mesons have very short lifetimes. Which means that they cannot go a big distance away from the proton that produced them.

Indeed, as we remember, the dimensions of the pi-meson cloud about the proton are very small, of the order of 10^{-13} cm. Unlike the electron, the proton is only very slightly smeared out by pi-mesons. But we know that protons are rather energetic in their interactions with K-mesons as well. That explains why a proton can also have a virtual cloud corresponding to this interaction, a K-meson cloud. Since the rest energy of a K-meson is some three times that of the pi-meson, the K-meson cloud should be just that number of times smaller and should be located inside the pi-meson cloud. Still deeper in the interior we should find the concentrated 'trembling' proton that decays virtually into proton-antiproton pairs.

Physics thus arrives at the startling and inevitable conclusion that the structure of particles of the microworld is a reflection of all their interactions with other particles. The essence

of microparticles turns out to be very fluid and mobile.

This conclusion ceases to be unusual if we grasp the idea that particles do not exist without their interactions. All microparticles are interrelated by interactions. Interaction of particles is not something introduced from the outside, but is an integral and natural part of their structure.

Yes, the structure of a particle at any time is determined by all of its interactions. Conversely, the character and degree of interaction are determined by the structure of the particle. That is the dialectic essence of matter and the field, the properties proper of particles and their interactions, and the inseparable generality of the inseverable community of the microparticle and of the entire universe.

Old Ideas Hold One Back

This constant and ubiquitous relatedness of matter and field confronted physicists with the task of interpreting it and generating new concepts to describe the matter-field unity. Here, quantum mechanics with its established notions was rather on the conservative side.

When quantum mechanics originated, it inherited from its predecessor, classical physics, all the concepts used in respect to the world of ordinary things and carried them over into the world of the ultrasmall. The Schrödinger equation was constructed along the lines of the classical wave equation with the sole difference that it described not ordinary waves but 'waves of probability', which expressed the law of

motion of microparticles in space and time. At first the satisfaction was complete, the microparticles willingly obeyed these laws.

True, from the very start of quantum mechanics it was found that these old concepts would not function well in the new physics. The uncertainty relation made it evident that the earlier ideas of exact position and velocity, particle energy and time could be applied in the microworld on a very restricted scale.

This half-hearted satisfaction gave way to dissatisfaction as soon as the microparticles gained energy sufficient for mutual transformations. The above-described method for establishing the laws of motion of particles in space and time broke down completely.

Just picture the situation: there is one particle, then we get another one, or several even, or in place of particles we have photons. Quite naturally, the wave function was not in a position to describe conversion. According to quantum mechanics, transformation should take place at a single point of space and instantaneously. As a result, we get another particle or a photon for which the earlier wave function does not hold any longer.

What did quantum mechanics do in that case? At the site of conversion, it combined both laws of motion (old and new) taking advantage of the familiar laws of conservation of energy and momentum.

In this approach, the process of transformation itself was left out of consideration. Firstly, because it occurs at a single 'point' in space and also in time so that at the instant of transformation the particle is not in motion in the ordinary sense of the word. Secondly, because one type

of particle vanishes and a different type of particle appears, yet the equations of motion referred always to a single invariable type of particle.

Which means that this classical approach to phenomena of the microworld carried over into quantum mechanics by means of the space and time concepts was clearly insufficient. It did not reflect the basic essence of this world, the transformations of particles into one another and into field quanta, and also the reverse conversion of quanta into particles of matter. The problem now was to determine the actual course of transformation. But this required a radical change in the mode of description.

Quantum mechanics did this by introducing those virtual processes that we have spoken about. They too fail and do not yield a final solution to the problem. A still more profound approach is needed in which the classical conceptions of space and time will probably undergo fundamental change.

The Reverse of the Obvious

How to begin this new thing? Some say: give up the notions of space and time as such.

Hardly! Physics would then find itself in difficult straits, for the existing concepts of the microworld, despite their unusual nature, are still based on our customary notions about space and time. It is indeed hard to reject such fundamental ideas which we are used to from the first day of our life. On the other hand, space and time are needed anyway to describe phenomena in the microworld that are not associated

with transformations of particles, for these concepts are very convenient here.

There is another, more realistic, approach: revise our concepts of space and time. Einstein did this for the first time half a century ago. Now we have to supplement Einstein's views. which apply to the world in the large, with the peculiarities of the world of the ultra-small.

What is the true essence of space and time? They are so familiar that we never give them thought. To our everyday mind, space is a repository of bodies. Nothing more? Just think for a moment where the concept of space comes from. From the very start, man deals not with 'pure' space, but with the bodies that fill it. Bodies, objects are perceived by sight. Objects appear to us to be close if they occupy a large field of view in our eye. Yet this is nothing other than a large number of photons emitted by the body and impinging on our eye. In other words, the stronger the electromagnetic field (created by a body) in our eye, the closer the object appears to us. And vice versa, few photons entering our eye indicate that the object is either small (with few atoms emitting photons) or far away (few photons of the total number reach our eye).

If man were possessed only of eyes from birth, he would never be able to distinguish between small close-lying bodies and distant but large objects. With the eye alone, that is, without any other mental operations, it is impossible to determine how far objects are from us and what their dimensions are. We are aided by the sense of touch. We touch objects and learn

about their dimensions (relative, naturally—as compared with ourselves).

If there were no objects, we would have no conception of space. At night, when we do not see objects, the feeling of space is lost.

Our sense organs that help us to build up conceptions about the world around us are actually instruments. They are even sensitive enough to register quantum events. But the world is so constructed that many thousands of millions of such events are registered at one time. The result is that our sensations (and conceptions) are 'averaged' (or classical, as the physicists say). The unusual nature of quantum laws is displayed when these events are studied singly.

Space is not the only thing of material origin in our minds. If we found ourselves in a situation where nothing changed around us (this occurs deep underground and will probably be the case of future astronauts who will be moving at great distances from astronomical bodies and for many years at a time), we would lose all perception of time, and hence any conception of it.

We have already mentioned the fact that there are two kinds of time in principle: the 'proper time' of a body determined by the physical (and chemical) processes in that body, and the 'general time' determined by large assemblies of bodies. As a result, just as there is no space divorced of bodies, so there is no time divorced of events.

The course of time is determined by events, concatenations of cause and effect. The more active the events in some system of bodies, the faster they follow one another (in other words, the more intense the interactions in that system), the 'faster' time flows in the system.

It will be recalled that this conclusion is corroborated even in our own experience. A day filled with events flies by in 'no time', while one without any events 'drags along'. Underlying this subjective impression is a very profound objective foundation.

The Ubiquitous Quantum

These new conceptions of space and time are not yet accepted by all physicists. What is more, they have not yet been confirmed experimentally.

They appeared over thirty years ago, but have not yet gained general currency. However, many scientists believe that they contain some of the truth.

The basic proposition concerning the relationship of space and time with the existence of bodies and their motions in the microworld is something like this: since microparticles and their motions have quantum properties, space and time should be quantized as well. And if that is so, then the last stronghold of classical conceptions will crumble. Space and time will lose their continuity and will break up into minute discrete 'portions'!

What this means is that there should be special kinds of 'cells', so to speak—the quanta of space and time. Their dimensions would perhaps be determined by the masses, energies, momenta (and possibly other characteristics) of microparticles. Quite naturally, these cells would have to be the smallest of all possible quantities.

But so far we have no knowledge of any such 'elementary length' or 'elementary interval of time'. Which might mean that they lie beyond the sensitivity of the most exact modern methods

of measuring lengths and times in the microworld. The limit of these techniques is, for length, of the order of the range of nuclear forces, or 10^{-13} centimetre, and for time, of the order of the 'nuclear time', i.e., 10^{-23} second. Some scientists believe that the 'length quantum', if it exists, should be hundreds or even thousands of times shorter.

Very interesting conceptions. It is understandable why we never notice the existence of quanta of space and time. They are simply too small. No timepiece can measure a fraction of time of, say, one millionth of a millionth of a millionth of a millionth of a second. And the same goes for lengths, the same fraction of a centimetre!

But even if we could measure such fantastic fractions of space and time, we would never be able to actually do it. Instruments are crude things, they change the microworld in the act of probing it. Recall, finally, that our classical concepts of length and time in the microworld are limited and hold true only to a certain extent. These limits become a dual matter-field aspect of microparticles. And yet these very same limits are the quanta of space and time that we have been talking about.

Then is there any sense in introducing such cells or quanta of time? For don't they continue to reflect our everyday conceptions about space and time?

That is true enough. We have mentioned off and on that each new layer of knowledge makes its appearance not in a void but on the foundation of earlier layers. The extremely exacting process of developing new conceptions does not take place overnight, it is slow and the new

notions will always bear traces of their predecessors. The birth of new concepts is always a travail.

So it was in the first years of quantum mechanics, and so it continues to be now when quantum mechanics is confronted with still greater barriers. Will it be victorious, or will it succumb, supplanted by a new and more powerful theory?

From Quantum Mechanics to...?

Indeterminable Determinacies

Mass, charge, spin, parity. Give exact definitions of each of these particle characteristics! And make the definition independent, that is, do not express one quantity in terms of another, say, mass in terms of the force of weight, or charge in terms of the force of attraction and repulsion.

You won't get far if you do. We are always using these concepts but not a single physicist in the world today knows what they really mean 'deep down'.

That is the situation of quantum mechanics as of today. It makes extensive use of things like mass, charge and other ideas borrowed from classical physics. And it discovered some new things of its own that describe particles—spin and parity, for instance. But it can say no more about the origin of these features than it can about the origin of mass and charge.

Indeed, what is mass? There are two answers. First: mass is a measure of the quantity of matter in a body. It may be understood as the quantity of atomic nuclei (since they contain

the bulk of the mass of atoms) in a given volume of substance. In turn, the mass of the nucleus may be interpreted as the quantity of nuclear particles, protons and neutrons.

But then what is the mass of a proton? Is it a measure of the quantity of matter in it, as before? What measure? What matter? The very concept of measure indicates that something can be broken down into smaller fractions. But it would appear that the proton is not divisible any further. And we can only guess what the matter in the proton is like.

When we say that the proton has a mass of approximately 10^{-24} gram, we only mean that one gram of substance contains roughly 10^{24} protons. Thus, to define mass as a measure of substance for protons and other microparticles is rather meaningless.

The second definition of mass is that mass is a measure of the inertia of a body, in other words, a measure of the resistance the body offers to any change in its state. In the most elementary case, mass determines the resistance of a body to any alteration in its position in space.

Then, perhaps, we should understand the mass of a proton as a measure of reluctance, as it were, to be set into motion by forces due to other particles. This definition is not satisfactory either. Forces represent interaction, in the final analysis the action of a field. When a proton increases its speed, it acquires extra mass from the field; when its speed diminishes, it returns this mass to the field. Small as these portions of acquired and lost mass may be, they do exist. Hence, mass is a variable quantity and thus loses its property of a definite measure.

Thus we find in the microworld that mass itself has to be measured with something. In our case, the mass of the proton, in accordance with the equations of relativity theory, is determined by the rest mass of the proton and the ratio of its velocity of motion to the velocity of light.

There seems to be a ray of hope. The rest mass is indeed an invariable quantity for a given type of particle. If it is changed, the particle changes. Doesn't it then follow that the rest mass is also a measure of inertia? However not with respect to ordinary mechanical motion—translation in space, but with respect to motion in the very broadest sense of the word—to the transformation of particles.

This would seem rather close to the truth. We recall that when the kinetic energy of particles is compared with their energy proper as determined precisely by the rest mass, particles obtained the possibility of actual transformations into the quanta of its field.

But if this is so then the rest mass becomes a measure of the qualitative stability of particles. For some particles this mass is not very great and conversion into quanta can begin at rather low energies. In the case of other particles, it is much greater, and accordingly the particles are considerably more stable.

On the present view, particles experience actual transformations and also so-called virtual transformations that underlie their interactions. Thus mass acquires yet another aspect in determining the energy of the virtual quanta of fields.

All this makes mass a very intricate concept. On the one hand, mass is some kind of character-

istic of the particle as such; on the other, mass is a determining factor in all interactions of the particle.

Undoubtedly, the other particle characteristics should be just as complicated. Today, all the problems involved in determining the deep inner essence of entities of the microworld come up against this greatest of unconquered peaks of physics—the interrelation of the two basic forms of matter, substance and the field.

Particles of substance possess properties of the field. Field quanta have material properties....

Which is the 'most fundamental', which is primary—substance or the field?

A century ago, when physics had just acquired the concept of the field, the answer was obvious: substance of course. The particles of a substance generate a field about themselves. The field is only an auxiliary tool for handling particle interactions. There is no field without matter.

But time passed, and it was found that a field could generate particles, that particles could vanish and become a field. Not so auxiliary as might be supposed!

Then physicists went to the other extreme. Taking Einstein's cue, they stated: the field is primary—the unitary universal field in all of its multifarious manifestations. Particles of matter are simply 'blobs' of the field. There is no matter without the field.

Einstein spent many years working on a unified field theory that would incorporate all known types of fields and particles, but all his attempts failed. Physicists gradually came to the view that neither field nor substance is primary, that both in equal measure are the fundamental and primary aspects of matter as such.

That, it turns out, is the correct view, and the argument between adherents of the unified field and unified matter could cease. Yet physicists continue to argue: How correct is their knowledge of the world of ultrasmall things? Do their concepts correspond to the true essence of these entities? Are they not mistaken in imposing on nature theories thought up by the human mind? And is man—a representative of the world of large things—at all capable of knowing things and events that occur in the microworld of atoms, nuclei and elementary particles?

Man is able to learn the laws of nature and get closer and closer to the truth. But the process of cognition will never come to an end, no knowledge of the world will ever be absolutely exact.

Taking these propositions as his foundation, the physicist approaches the problem of how he should understand the interrelations of the two basic forms of matter.

First of all: Can there be a unified field or a unified substance? No. Field and substance are two opposed forms of the existence of matter and its development. One is impossible without the other. Two sides of one medal. Though opposite, they are unitary and inseparably connected: the field has the properties of a substance, and a substance has the properties of the field.

Do our notions about the existence and interconnection of these two forms of matter possess any degree of truth? Yes, they definitely do, since these concepts, though inexact, are nevertheless correct, on the whole. As a rule, observations fit into their framework and predictions based on them hold true.

Then why do physicists continue to argue as to how one should interpret the results they obtain? First of all, because not all physicists are acquainted with dialectical materialism. Hostile philosophies, especially the most noxious trend called subjective idealism, maintain that the world exists only in man's imagination so that the laws of nature are at best only the workings of the human mind. With a philosophy like this, even some prominent scientists are not inclined to attach much real significance to the discoveries of physics. These scientists regard the world as unknowable.

This is all the easier since the world of the ultrasmall cannot be observed directly, one cannot see it so as to be convinced of its existence. And—still more important—the properties of the microworld differ radically from those of the customary world about us. This difference is so great that our everyday conceptions do not reflect the real essence of the microworld.

Science develops in such a way that new conceptions originate very slowly. After all, human beings live in the world of ordinary things, common notions, and their minds hold tenaciously to these notions. It is very difficult to make the translation to the 'unconceivable' conceptions that make for a correct picture of the microworld. But one has to. It is so inconvenient to speak and think about a 'microparticle' that is not simply a particle, and to talk about a 'field' that is something more than a field. The trouble here is not so much in the words used, but rather in imagery, in conceptions and notions.

Quantum mechanics was able to combine the old concepts into new particle-wave, positron-hole and meson-quantum images. But in the

minds of physicists these dual entities have not fully merged into unified actuality.

This merging is a matter for the near future.

The Biography of Quantum Mechanics

During the sixty odd years of its existence, quantum mechanics has passed through three stages of development.

The first stage is from Planck to de Broglie, and embraces 25 years—from the discovery of the material properties of light waves to the discovery of the wave properties of material particles. During these years, Einstein and Bohr developed the theory of particles of light (photons), the first very imperfect theory of atomic structure and of atomic phenomena.

The second stage in the development of quantum mechanics began with de Broglie's discovery in 1924. Within the exceptionally short period of about 5 years was created the basic 'working tool' of the new theory. Dirac synthesized quantum mechanics and Einstein's relativity theory. During the period up to the Second World War, the theory of the atomic nucleus was created.

And, finally, the third period—after World War II—quantum mechanics was extended to the elementary particles and to the second basic form of matter, the field.

During this third stage, quantum mechanics come up against ever greater difficulties. After the brilliant victories of its early years came a series of setbacks and failures.

The impression is that, good as it is against atoms and molecules, it is simply not strong

enough for those extrahard nuts—the structure of elementary particles and their interactions.

Experiment today has gone out far ahead of theory. Theory has yet to interpret processes in the deep interior of atomic nuclei. On the agenda are problems dealing with the very essence of the concept of elementary particles.

Quantum mechanics has not yet succeeded in resolving these problems. Its limitations, which twenty years ago had seemed so hazy and distant, are now becoming ever clearer. The time is ripe for a rejuvenation of quantum mechanics.

Isn't this reminiscent of the situation at the turn of the century with regard to classical mechanics?

On the one hand, there don't seem to be any facts that run counter to the basic propositions of quantum mechanics. It is only an inability to account for a number of phenomena, an inability of the theory as such, not of the scientists behind it. Maybe what is needed is an extension of the framework, perhaps new important noncontradictory propositions need to be added to give the theory strength.

Yet it may happen that these propositions will not jibe with earlier ones. Then for a time we will be discouraged. There have never been all-powerful theories and there never will be. Like life generally, each theory has its shaky childhood, its strong youth when it resolved dozens of extrahard problems, its calm maturity when forward movement slows down and the theory spreads out encompassing ever broader spheres of phenomena, moving into technology and industry and establishing contacts with other disciplines, and finally old age when it

is powerless against the onslaught of fresh facts, facts discovered by the theory itself.

Then a period of stagnation sets in. At least it would seem so, yet that isn't the situation at all. New ideas are all the time cropping up that find the framework of the old theory too narrow. One fine day these new ideas will break the shell in which they have been confined, and science will then make a big jump forward.

On the age scale we have just described, quantum mechanics today has reached its peak of maturity and old age is creeping up. It is connected with numerous important technical achievements, it has handled problems ranging from the structure of stellar systems to that of atomic nuclei and the elementary particles. Today, quantum mechanics is the strongest physical theory of the microworld.

There is no theory that can compete with it, but there is definite need of such a theory. Scientists at work in this field of physics are trying either to rejuvenate it with new content that does not contradict its basic principles, or to change its spirit and give it up for more radical things. Let it be sacrificed, they say. Yet none can boast of any success.

More and more physicists tend toward the view that what is needed is something still more unusual, a 'crazier' theory! No one is afraid of that word, for anything fundamentally new encounters terrific resistance from the old. There are always those who suggest psychiatric treatment for the author. It was the same with quantum mechanics when it was born. It too was called 'crazy' by many. But now there is probably not a single scientist that does not accept it.

However all this may be, there is one thing that is certain: physics is on the threshold of a new big advance. This leap is not into the dark, for scientists see very clearly the route which the new physics must follow and the stations along the way.

Here are some of them. A rigorous unified systematic arrangement of all known and unknown elementary particles. The structure and internal properties of particles of matter. The nature of the forces operating in atomic nuclei. Exact laws of interrelationships between the two fundamental forms of matter—substance and field. The mutual relationship and interdependence of all the properties of moving matter: energy and time, mass and space, and the specific essence of the microworld determined by this relationship.

We have described in this book how quantum mechanics was born and how it grew up, how it become the powerful weapon of science that it is today. We have told how quantum mechanics is handling the present problems of physics and how it is seeking ways into the still smaller world of things, the ultramicroworld. This world of new smallness is the problem of today.

Quantum Mechanics Gets Its Second Wind

Every science has two lifetimes. The first has to do with ideas, conceptions, laws and formulas. The second has to do with their translation into the hardware of technology—tools and instruments and machines.

No matter how abstract the gyrations of the scientific mind, there is always a return to the

real world of human beings and to their needs.

Marx' famous words that philosophers only explained the world, the point however was to change it, do not refer to philosophy alone. They contain the true meaning of the existence and development of any science.

Every new discovery is an addition to the storehouse of human knowledge. But it is not only that. Man becomes stronger in his struggle with nature. If one traces discovery throughout history, he will see that in each later period the gap between a big discovery and its application to human needs becomes shorter and shorter.

Science perceives future problems before human practice gets to them. This foresight is not a favour of the gods or of geniuses, it is objective reality, at the heart of which lie the laws of development of society.

Science does not wait for a vitally important problem to mature. Whether scientists realize it or not, they attack fresh problems long before they have become of vital importance.

Science is the most forward outpost of human society, the scout of the future and the most reliable defender of the present.

The discovery and development of quantum mechanics may serve as a good illustration. Let us take a look at the second lifetime of quantum mechanics.

Atomic nuclei were conceived round about 1912. Twenty years later, that conception took on clear-cut outlines. The particles that make up the nucleus were defined and the forces operative between nuclear particles were discovered and explained. The 'inaccessibility' of the atomic

nucleus, both physically and conceptually, did not deter physicists. Thirteen years later saw the advent of the atomic age. True, in the form of ghastly atomic bombs which the Americans dropped on Hiroshima and Nagasaki bringing death and destruction instead of abundance. Then just a few more years passed, and in 1954 the Soviet Union put into operation the world's first atomic power station. The Soviet scientists diverted the power of the atom from war and destruction to peace and construction.

Quantum mechanics found its first technical application in the inferno of the atomic reactor, where streams of neutrons split up the nuclei of heavy atoms and generate heat and electricity.

Scientists then turned to the light nuclei, the isotopes of hydrogen, in attempts to extract more energy. The Soviet Union aims at the utilization of thermonuclear reactions for peace, for generating electricity. This is the noble aim of the Soviet scientists—to supply humanity with power for thousands of years to come.

Here, too, quantum mechanics has important things to say. It calculates the course of fusion reactions and predicts the energy that will be generated.

What next? Fresh problems. Problems that will be much more difficult than what we know today. But then scientists of the future will be better equipped than they are today.

Up until recent times, researchers rarely gave thought to the consequences of their discoveries. Young A. Ioffe who at the beginning of this century became interested in so-called waste materials could hardly have imagined the future of semiconductors.

But without quantum mechanics semiconductors would be dead. Quantum mechanics not only explained their remarkable properties, it suggested radical ways of improving them. Today, the department of quantum mechanics known as the band theory of solids has become the guiding star for many thousands of research workers and engineers in electronics.

These minute yet powerful electronic devices have wrought fundamental changes in industry and technology. Not a single factory or vehicle or communication facility does without them. There is hardly a single sphere of human activity that has not experienced the effects of electronics.

Scientists are already working on one of the boldest projects of all: the use of semiconductors to extract electricity from the solar energy that falls so generously on the earth, and thus take over from the nearly exhausted fossil-fuel sources of energy. The first semiconductor solar batteries are already functioning generating electric energy out of the sun's rays. Designers are working on projects for solar batteries to power the first settlements on the moon and the planets of the solar system.

An interesting feature in this respect is that on the earth semiconductor facilities covering large areas (this is necessary to catch a large enough portion of the sun's rays) would interfere with plant growth and livestock farming. On the moon there would be no such problem.

Then how would we transmit these huge quantities of energy to the earth? Transmission lines as we know them here on earth would naturally be out of the question. What is more, the losses

are very great in these conventional modes of transmitting power.

Some ten years ago a prominent Soviet physicist V. Fabrikant proposed a quantum amplifier of electromagnetic waves. And quantum mechanics, first translated into the hardware of a quantum amplifier and later into a quantum oscillator, brought to life a whole series of devices—the masers (amplifiers and generators of radiowaves) and the lasers (amplifiers and generators of light beams). That is what you call science fiction come to life.

At the beginning of the book we spoke about the laws of quantum mechanics that govern the electromagnetic radiation of atoms. These laws were firmly established long ago, so long ago (nearly thirty years ago—quite some time in quantum mechanical history) and so firmly that in the 1950's few people ever gave them thought any more.

But then inquisitive researchers took a fresh look from a new angle, and these laws scintillated quite unexpectedly giving birth to a new set of amazingly powerful instruments.

We have touched on only a few of the more exceptional technical achievements due to ideas and conceptions about the world of ultrasmall things that came with quantum mechanics. Quantum mechanics continues to make inroads into technology and industry. The number of devices continues to grow. This second lifetime of quantum mechanics is exceptionally rich and diverse. We have witnessed its inception. The future should exceed the predictions of the wildest science fiction.

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The author of this book, Vitaly Rydnik, is a physicist who graduated from the physics department of Moscow University in 1951. Since then he has written a number of books popularizing science—"In the World of Simple Wonders", "The Fourth State of Matter", "Particle Hunters", "The ABC's of Quantum Mechanics". Rydnik has also written extensively for Soviet scientific-technical journals and popular science magazines. The present book has been specially revised for this English translation.